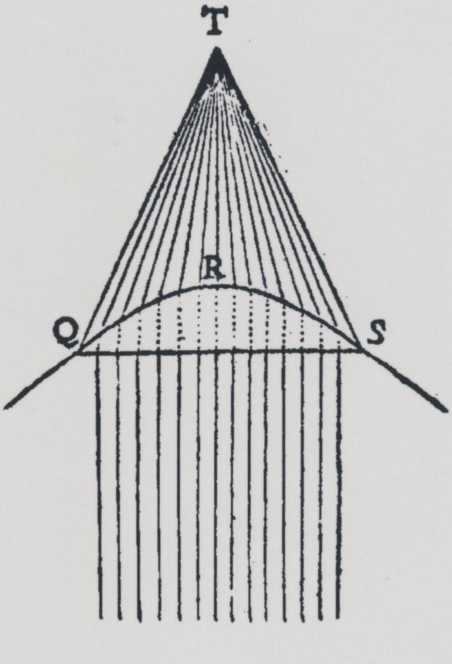
DESCARTES
AND THE HYPERBOLIC QUEST



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in the Seventeenth Century

D. Graham Burnett

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Introduction

On November 13 of 1629, René Descartes posted a long letter from his self-imposed exile in Holland back to a young instrument maker in Paris named Ferrier.[1] The letter and its dozen diagrams offered detailed instructions on how to build a new and secret machine, a device that promised fame (and perhaps wealth) to its inventor and to the man who succeeded in realizing it. It would not be easy to make it work, but Descartes believed it would transform the study of the physical world, and he closed the letter with a warning coupled to an enticing suggestion:

> In closing, do not hope by this machine to perform marvels at your first try, I am warning you so that you do not build yourself up on false hopes and so that you do not even attempt to undertake this project unless you are resolved to spend a great deal of time upon it. But if you have a year or two to apply yourself to all that is necessary, I would hope that we might see, by your efforts, if there are animals on the moon.[2]

The machine that promised such wonders was a mechanical device for making a new and more powerful telescope lens (ground to the

[1]Descartes' work with Ferrier (see chap. 2 below) has been reconstructed primarily from the correspondence in *Oeuvres de Descartes*, edited by Adam and Tannery. Translations are mine, unless otherwise noted. Shea has offered an interpretation of these materials in his "Descartes and the French Artisan Jean Ferrier," and in a section (pp. 193–201) of his *Magic of Numbers*. Shea follows Jules Simon (and others) in giving "M. Ferrier" the name "Jean." Compare Daumas (*Les Instruments Scientifiques*) who follows Nachet (*Instruments scientifiques et livres anciens*) and gives Ferrier's likely first name as Guillaume (see p. 98). Gaukroger (*Intellectual Biography*), who offers a brief and clear treatment of the machine and the anaclastic (pp. 190–95), agrees (see p. 438, n.23). Daumas identifies three Ferriers working as mathematical instrument makers in the period in Paris: Antoine (c. 1608, mentioned by Turner in "Paper, Print and Mathematics," p. 35); Guillaume (c. 1620–1640); and Jean (c. 1641, known on the basis of a single graduated circle in collection of the Académie [no. 428]). As this book went to press, Jean-François Gauvin generously shared with me his finding that Jean-Baptiste Morin referred to the Ferrier who worked with Descartes as "D. Ioannes Ferrier" in a 1634 publication (see Mersenne, *Correspondance*, Vol. 1, p. 516). This seems to settle the matter, but I have nevertheless retained my convention of omitting his first name in this study. For other mentions of the machine, see De Waard's "Notes sur le Rodage" in Vol. 3 of his edited *Journal tenu*; and Korteweg, "Notes sur Constantijn Huygens," especially pp. 435–37. For a general discussion of Descartes' work with artisans, see Belgioioso, "Descartes e gli artigiani." Descartes' biographers have generally at least touched on the machine and Ferrier, e.g., Baillet, *Monsieur Des-Cartes*, pp. 181–84, 215–22; Adam, *Vie et Oeuvres*, pp. 90, 107, 188, 470; Haldane, *His Life and Times*, pp. 121ff. See also the references in *His Life and Thought* by Rodis-Lewis.

[2]Adam and Tannery, *Oeuvres de Descartes,* Vol. 1, p. 69.

shape of a hyperbola), which Descartes believed would vastly surpass handmade spherical lenses in clarity and resolution.[3]

The aim of this book is to examine this machine—its conception, the labor expended on its realization, and ultimately its resilient legacy—in the broader context of seventeenth-century optics, instrumentation, and mechanical craftsmanship. It is my intention to show that the history of this device sheds light on several important areas: on the history of telescopes in the period, on the relationship between instrument makers and mathematical adepts, on the mechanical philosophy and its connection to machines, on the thought and work of Descartes himself. Gaston Milhaud, writing in 1921, declared that the fanciful machine "passed as if it had never existed."[4] It will be my purpose to show just how far this assessment strays from the mark.

Pushed by the promise of lenses designed on the basis of optical principles (rather than left to what he conceived of as the vagaries of artisanal craft), Descartes directed at least five different artisans over the course of fifteen years in the hopes of perfecting a machine to grind hyperbolic lenses. The project endured virtually the full course of his scientific life and even compelled him to apply himself to the task with his own hands. His surviving correspondence contains more than fifty allusions to the enterprise, including at least eight full letters devoted to it. Moreover, while the machine itself remained unrealized (despite the efforts of a number of skilled turners and mathematical practitioners), the publication of its design as the culmination of *La Dioptrique* in 1637—coupled with a challenge to "the most curious and the most skilled of our generation" to undertake its realization—gave rise to considerable and enduring speculation, tinkering, and controversy.[5] Interest in the project of hyperbolic lens making lasted through the century and absorbed the attentions of major scientific figures, including Hevelius, Huygens, Maignan, Wren, and Newton.

The filiation of the machine's significance can be spliced into two distinguishable threads: on the one hand, the machine embodied the promise of aspherical lenses (those with surfaces of parabolic, ellipsoidal, or hyperbolic section); on the other hand, the machine promised

[3]The lenses in question here represent hyperboloids of two sheets, see Hilbert and Cohn-Vossen, *Geometry and the Imagination*, pp. 13–15.

[4]Milhaud, *Descartes Savant*, p. 196.

[5]Adam and Tannery, *Oeuvres de Descartes,* Vol. 5, p. 227. For a discussion of *La Dioptrique* as a practical manual of instruction for controlling nature, see Ribe, "Cartesian Optics." Elements of this argument can be found in an earlier piece by Eastwood, "Descartes on Refraction." Ribe mentions the lens machine and Ferrier (p. 56), but it is curious that he does not see the machine itself as the culmination of the very project of "practical mastery" that is his subject.

lenses made without hands—that is, made "automatically" by a self-regulating lathe. These two aspects of the machine were related: it was precisely the purported complexity of aspherical surfaces that demanded, in Descartes' view, a mechanized system of lens grinding. Nevertheless, over the course of the century savants and turners applied themselves to mechanical systems for making "traditional" spherical lenses, and, at the same time, the optical grail of an aspherical anastigmatic lens (one that focused all incident parallel rays of light on a single point, which a biconvex or plano-convex lens of circular section did not do) continued to be pursued by a variety of methods, including handcraft techniques that relied on a minimum of mechanization.

The longevity of both endeavors is all the more striking in view of their very limited success: aspherical lenses were much discussed but seldom seen; those few that were realized distinguished neither themselves nor their makers. More interesting, perhaps, in the annals of failure, is the durability of the program to mechanize the making of optical lenses of all kinds. For, despite dozens of zealous efforts throughout Europe all through the century, mechanical systems for grinding lenses failed: none ever produced a lens that made any significant discovery or surpassed, in competition, a handmade lens produced by a skilled artisan. In 1699 the very best lenses were being made using only slight variations on the handcraft techniques of the sixteenth century. The lenses were spherical in form, formed individually, by hand. Better attention to grinding and polishing media, as well as some small changes in craft practice, accounted for the improvements in lenses from the beginning of the century to the end, while the complex and elegant mechanical devices for grinding lenses—systems that preoccupied theoreticians and mechanical adepts for the whole of the century—never proved the equal of craft practice. In fact, there are only a few scattered references to lens making machines actually making lenses of any kind, much less lenses that could take their place beside the artistry of Italian lens makers like Eustachio Divini and Giuseppe Campani.

It is here that a foray into the (easily maligned) "history of fancy and useless instruments" may, paradoxically, be quite useful indeed.[6] Understanding the appeal of mechanical lens making systems demands consideration of the history of the lathe, the traditions of mathematical instruments, theaters of machines, and automata. In

[6]Van Helden, "Telescope in the Seventeenth Century," p. 47.

return, reflection on these systems leads to insights into the processes by which the new optical devices came to be understood as reliable, truth-seeking instruments; into the intricacies of the relationship between instrument makers and their users; and finally, into the nature of the mechanical philosophy. Catherine Wilson has called for "an examination of the interaction between the history of science and the history of technology that takes into account the problems that arise in connection with the idea that science based on the use of machines and instruments gives a truer, better, or deeper account of the world."[7] In examining these very issues this book proceeds in three chapters: In chapter 1, I offer a context for Descartes' machine by first sketching a brief outline of lens grinding techniques and technologies up to the 1630s, and then detailing several mathematical and mechanical traditions on which the machine itself can be seen to draw. Chapter 2 turns to a chronological account of Descartes' work to realize the machine, beginning with his correspondence with Ferrier, and following the project through to the efforts of Constantijn Huygens and those he employed. Finally, in chapter 3, I survey the other mechanical systems for lens grinding in the seventeenth century, paying particular attention to the legacy of Descartes' device. In the conclusion, I suggest, somewhat speculatively, another possible legacy of the machine, one that may reach into Descartes' own philosophical writings: Given the function of "hyperbolic doubt" in the *Meditations*, it seems necessary to ask whether this significant mental device (which served to "focus" the mind in such a way as to produce clear and distinct ideas) can be properly understood without reference to Descartes' other, and less ethereal, hyperbolic quest.

[7]Wilson, *Invisible World*, p. 70.

1

Lens Making in the Seventeenth Century: The Machine in Context

THE CRAFT OF THE LENS

In 1609 when Galileo Galilei trained a pair of lenses on the night sky, the telescope was an innovation but the lens was not.[1] Since the thirteenth century, artisan-opticians had made spectacles for the monks and elites in Italy, France, and Germany.[2] The artisanal craft of lens making, which grew to serve the needs of spectacle makers, could not, however, provide enough lenses of requisite quality to meet the explosive demand created by the new viewing tubes.[3] So powerful was the attraction of the new instruments that by 1617 Galileo's intimate friend Giovanfrancesco Sagredo was disappointed to discover that his correspondents in distant India were not surprised by the telescope he sent them—they already had enough to go around; by 1624 one wealthy savant in Europe had purchased more than forty of them.[4] The instant demand for the new optical devices—for both

[1]For a generally accepted account of the origin of spectacles, see Rosen, "Invention of Eyeglasses." Citations for a number of other relevant works (including those of Zecchin and Alberotti) can be found in Ilardi's informative "Renaissance Florence." For discussion of lenses, their manufacture, and use in the period immediately preceding the invention of the telescope, see Van Helden, "Invention of the Telescope," on pp. 9–19 (discussion) and pp. 28–45 (documents).

[2]Twyman, *Prism,* p. 9.

[3]For an indication of the difficulties experienced by Galileo in this regard, see Bedini, "Galileo's Scientific Instruments." For additional (general) references to the slow response of the lens crafting community to the rapid increase in demand for optical instruments after 1609, see Van Helden, " 'Astronomical Telescope'," p. 14; and Sluiter, "Before Galileo," p. 227. Also interesting on this subject is the recent unpublished paper by Dupré, "Ausonio's Mirrors."

[4]Bedini, "Galileo's Scientific Instruments," p. 101; King, *History of the Telescope*, p. 46.

terrestrial and celestial use—necessitated lenses, many lenses, ground to ever more demanding specifications, lenses from the size of a pinhead to lenses that required commandeered naval vessels for transportation.

What were the craft practices for lens making that antedated the development of the telescope? The earliest detailed discussions of the process appear in William Bourne's tract on enlarging lenses (composed around 1580) and Giambattista Della Porta's *Magia Naturalis* printed (in its most commonly cited form) in 1589, a book that went through more than twenty editions and was widely translated.[5] In book seventeen, entitled "Of Strange Glasses," Della Porta explains:

> It remains now to teach you how Spectacles and looking glasses are made, that every man may provide them for his use. In Germany there are made Glas-balls, whose diameter is a foot long or there abouts. The ball is marked with emril-stone round, and is so cut into many small circles, and they are brought to Venice. Here with a handle of wood are they glewed on, by Colophonia[6] melted: And if you will make Convex spectacles, you must have a hollow iron dish, that is a portion of a great sphere, as you will have your Spectacles more or less Convex; and the dish must be perfectly polished. But if we seek Concave Spectacles; let there be an iron ball, like to those we shoot with Gun-powder from the great Brass Cannon: The Superficies whereof is two, or three foot about: Upon the Dish, or Ball there is strewed white-sand, that comes from Vincentia, commonly called Saldame, and with water it is forcibly rubbed between our hands, and that so long until the superficies of that circle shall receive the Form of the Dish, namely, a convex superficies, or else a concave superficies upon the superficies of the Ball, that it may fit the superficies exactly. When that is done, heat the handle at a soft fire, and take the spectacle off from it, and joyn the other side of it to the same handle with Colophonia, and work as you did before, that on both sides it may receive a Concave or Convex superficies: then rubbing it over again with the powder of Tripolis[7] that it may be exactly polished; when it is perfectly polished, you shall make it perspicuous thus. They fasten a woolen cloth upon wood; and upon this they sprinkle water of Depart[8], and powder of Tripolis; and by rubbing it diligently, you shall see it take

[5]For a discussion of Bourne, see Van Helden, "Invention of the Telescope." Bourne's manuscript treatise is in the British Museum (Lansdowne MS 121), and has been transcribed and reprinted as William Bourne, "The properties and qualities." For Della Porta, see William Eamon, *Science and the Secrets*.

[6]"The dark or amber-coloured rosin obtained by distilling turpentine with water. Formerly also called Greek pitch (pix græca)." See OED s.v. "colophony."

[7]Diatomaceous earth.

[8]A "liquor of chymists" according to Bacon (1626). See OED s.v. "depart."

> a perfect Glass. Thus are your great Lenticulars, and Spectacles made at Venice.[9]

Della Porta's distinctive stew of Renaissance vitalism, Neoplatonism, and Neapolitan folk cunning contained diverse ingredients: this sober account of spectacle making had been stirred into a text that included several more colorful tips and suggestions, not least advice on making a magic rabbit-fat candle that, when burned, "constrains women to cast off their clothes and voluntarily shew themselves naked unto men." The eclectic quality of the *Magia Naturalis* (a classic of sixteenth-century tomes secreting *arcana naturae*) should not be taken to detract from its authority on the matter of lens crafting.[10] Indeed, Della Porta's account is echoed by that of his contemporary, William Bourne, writing in England around 1580:

> These sortes of glasses ys grounde vppon a toole of Iron, made of purpose, somewhat hollowe, or concave inwardes. And may be made of any kynde of glass, but the clearer the better. And so the Glasse, after that yt ys full rounde, ys made fast with syman vppon a smalle block, and so grounde by hande vntill yt ys bothe smoothe and allso thynne, by the edges, or sydes, but thickest in the middle.[11]

The best evidence for the faithfulness of these early descriptions rests on the fact that the craft of lens grinding changed little over the following century. From 1590 to 1690 spherical lenses were shaped by hand in metal forms by means of abrasive powders and polished by cloth, leather, or paper sprinkled with tripoli, much as Bourne and Della Porta describe.

Della Porta's book was not entitled *Natural Magic* because it contained a treatise on optics. All of the material included in the opus—from the monsters that could be achieved through interspecial animal husbandry, to the rabbit-fat candle, to a variety of concoctions to heal the love-worn and unloved alike—represented the intellectual exuberance of a hylomorphically inclined magus seeking out natural

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[9]Excerpted from the 1669 English translation of Della Porta's work. Published as John Baptista Porta, *Riches and Delights* (see p. 379). Della Porta first published a (slimmer) version of the *Magia Naturalis* in 1558.

[10]Van Helden ("Invention of the Telescope," pp. 15–19) discusses Della Porta's claim to have anticipated the discovery of the telescope. Although the claim does not stand, it both casts light on the peculiar complexity of the "prehistory" of viewing tubes (it is likely that compound "magnifying spectacles" had indeed preceded Lipperhey's revelation), and demonstrates that Della Porta did have practical experience with lens making.

[11]Bourne, "The properties and qualities," pp. 40–41.

powers, sympathies, and correspondences. A recipe book of popular remedies and ancient wisdom, *Natural Magic* purported to serve as a textbook for a nascent cunning-man who wanted to discover and trade in charms, incantations, and illusions. Despite his best efforts to defend his work as a rejection of supernaturalism and witchcraft, Della Porta spent much of his life parrying the charge that he was (as Jean Bodin put it) "un grand Sorcier Néapolitain."[12] That Della Porta, who finished his life in the shadow of the Inquisition, considered an accurate description of lens grinding techniques relevant to his broader intellectual enterprise gives some indication of the pedigree of the lens before the seventeenth century. Burning glasses and curious mirrors possessed powerful forces in the Renaissance worldview, and the craft of lens making sat comfortably in the same volume with a description of the occult virtues of a violin whose strings were fashioned out of viper entrails.[13]

The occult potencies of lenses, and the shroud of elliptical language that their manufacture seemed to demand, are revealed in the passage where Della Porta describes in cryptic terms the making of a lens that "burns to infinite distance" and may be used in "great and wonderful things, chiefly by inscribing letters in a full moon":

> Because a proportional radius doth proceed from the greater section, from the less is made the greater: to avoid this, make it of a Cylindrical Section, for it is the mean, and let it be set for the axis of the small and of the greater dissection, which may pass through the middle parallels: this held against the Sun, doth make refraction of the beams sent into it, very far and perpendicularly from the Center of the Cylindrical Section; and in this Art the reason cannot be found . . . For the beams passing through the narrow hole of a window, are forthwith dilated; nor is their proportion kept, by being far removed, wherefore it may reverberate and burn where the Cane seems clearest . . . . If the rays go forth above, or a little beneath, it is no matter, if not much money, or much money be laid out to make it. The making of it depends merely on the Artificer's hand; the quantity is nothing, be it small or great. The Latitude of the hollow is not necessary, onely let it be sent

[12]Eamon, *Science and the Secrets*, p. 202.

[13]Ronchi is best known for arguing that an Augustinian Platonism among scholars of optics from the thirteenth to sixteenth centuries inspired a mistrust of both sight and, a fortiori, lenses, which were conceived of as distorting screens. He extended this argument to explain the relative infrequency of references to lenses among these authors. See Ronchi, "A Fascinating Outline," pp. 527–32, 552–54; and "Altro è l'invenzione." In the latter essay he responds to the criticism of his account of European "lens-anxiety" offered by Lindberg and Steneck in their "Sense of Vision." Fiorentini and Maffei offer an interesting example of Galileo's attempt to deflect the concern that lenses distort vision. See their "Galileo's Brain," p. 78. For a recent treatment of these questions in general in the seventeenth century, see Wilson, *Invisible World*, particularly pp. 215–18.

> forth from the middle, that the rays may meet excellent well in the Centre. Let the window be open aflaunt, that it may receive a Parabolical Glass, and thus shall you have a Glass, if that be well done I spake of. *He that hath ears to hear, let him hear;* I have not spoken barbarously, nor could I speak more briefly, or more plainly.[14]

There is a danger of overstating the case for the hermetic descent of optical lenses, for spectacles had broad currency among elites in Italy and elsewhere from the mid-fifteenth century on, serving not only as aides to vision but also as very correct gifts of courtly patronage and as status symbols.[15] Moreover, understanding of the needs of different customers had led lens craftsmen in Florence and Milan to codify the types of lenses available into graduated categories correlated to the user's age, and hence to what would currently be understood as myopic stages. To some degree, the existence of such a well-established trade (and the businesslike manner of its transactions, as reflected in the correspondence cited by Ilardi) belies the claim that lenses resided only in the pantheon of natural magicians. Nevertheless, Della Porta and his treatment of optical tricks and potent lenses remain of particular interest in light of Descartes' knowledge of *Magia Naturalis* and his interest in its contents.[16] Beeckman and Descartes discussed this very passage concerning inscriptions on the moon sometime in the years 1628–29.[17]

The writings of Bourne and Della Porta offer a glimpse of the character of lens making crafts at the end of the sixteenth century, providing a context in which to situate the shifts that resulted from the development of the telescope. The work of Van Helden has substantially revised an earlier historiography of the telescope, one that cast its development in the seventeenth century as a product of the theoretical study of optics, implying that the study of light and the analysis of geometrical optics served as the basis of rational telescope design, with resulting improvements in telescope quality.[18] As Van Helden has shown, the physical form of the telescope emerged out of the

[14]Della Porta, *Riches and Delights*, p. 376.

[15]See Ilardi, "Doni di occhiali." Ilardi cites documents indicating that the Sforza court ordered more than three hundred pairs of spectacles over a four-year period in the 1460s.

[16]Gaukroger discusses the Jesuit predilection for the novelties of this text and those by Lull and Agrippa. He goes on to claim that Descartes' interest in optical illusions in his 1621 manuscript, "Observationes," derives from a reading of Della Porta. See Gaukroger, *Intellectual Biography*, pp. 59, 65, 129.

[17]See Rodis-Lewis, "Machineries et perspectives," p. 466, n. 28. Rodis-Lewis erred in asserting that Descartes had confused Agrippa and Della Porta in discussing the projection of writing on the moon; she appears to have sought the passage in the edition of 1561 (one of several she cites) where it does not appear.

[18]Dijksterhuis, exemplifying this tradition, went so far as to call the telescope the "fruit" of the development of geometrical optics.

manipulation of spectacle lenses, and an *opticus* of no particular theoretical distinction, Hans Lipperhey, is rightly credited with the innovation.[19] As for the actual improvements in telescope design—meaning the configuration and shape of lenses—that followed over the next century, even if some were discovered by the mathematically adept, just as many, if not more, were discovered by instrument makers and lens grinders of limited mathematical ability. Those that emerged from the work of natural philosophers (for example, Huygens' eyepiece of 1662) were discovered by them in their capacity as telescope makers and never stemmed from the application of an abstract or analytical theory of optics.[20] Two of the major proposed improvements in telescope design that did grow out of a developed optical theory, Descartes' hyperbolic lens and the reflecting telescope of Newton, both proved impractical to realize in the century and did not lead to better observational telescopes or better observations.[21]

It was not, therefore, rational telescope design or the mechanization of lens making that improved the quality of telescopes over the course of the seventeenth century but rather improvements in the quality of lenses, particularly the large, long-focus objectives.[22] Yet if Nicholas Hartsoeker ground the lenses he provided to the Académie in 1699 using essentially the same method described by Bourne more than a century before, then what accounts for the dramatic increase in the resolving power and clarity of telescopes over the seventeenth century, an improvement that played a major role in shaping the new sciences?

Refinements of the craft practices of lens making were primarily responsible for the improvements in telescopes in the seventeenth

[19]For details on the claim of priority, as well as Van Helden's admirably clear discussion of the necessary preconditions to the discovery (namely, the changing focal lengths on corrective spectacle lenses for both myopia and presbyopia), see Van Helden, "Invention of the Telescope," pp. 11ff.

[20]Ibid., p. 48.

[21]The only possible exception to the general statement that "rational" telescope design did not play a role in actually improving the quality of telescopes used in the seventeenth century might be Kepler's description of the astronomical telescope (making use of two convex lenses instead of the convex/concave combination of the Galilean telescope) in his *Dioptrice* of 1611. However, although Kepler did suggest the promise of such an instrument, his optical theory, without Snell's law of refraction, lacked the "rational," deductive character that Dijksterhuis claims moved the telescope forward. Moreover, the Neapolitan lens maker Francesco Fontana claimed to have built such an instrument as early as 1608. See Van Helden, "Telescope in the Seventeenth Century," p. 41; and " 'Astronomical Telescope'," pp. 15–23.

[22]"[I]t is fair to say that between 1610 and 1660 the improvements made in the telescope were due almost solely to improvements in lens grinding techniques." Van Helden "Telescope in the Seventeenth Century," p. 45. "[T]hroughout the seventeenth century, optical glass was produced by traditional methods." Bedini, "Lens Making for Scientific Instrumentation," p. 687.

century.[23] In the delicate grinding of a precise lens, subtleties of technique made the difference between lenses that were worthy of the master astronomers like Cassini and those destined for the spyglass of a military officer. The quality of the glass, the grain of the abrasives used to shape and polish the glass, and the intangibles of careful artisanal practice separated superior lens makers from the ambitious spectacle maker attempting to expand into a new and potentially lucrative market. A single missized grain of abrasive that found its way into a later phase of grinding would scar the surface of the glass; excessive polishing to fix such scratches would distort the shape of the lens. The master lens crafters paid extremely close attention to such subtle details as the careful washing and levigating of emery and the preparation of the smooth, even sheets of blotter paper used in the final stage of polishing. A few technical innovations also contributed to the improvement in the lens makers' craft in the seventeenth century. For instance, the refinement of a simple lathe for the cutting of the brass pans used for lens shaping, and the modification of the jeweler's polishing wheel, both contributed to the production of increasingly accurate and powerful lenses by artisans.[24] These devices and the critical refinements of craft practices gradually emerged in response to the demands for ever better lenses.

Although the improvements in craft practices may have been the work of artisans, the drive for better lenses lay in the demands of natural philosophers and professional astronomers. Those anxious to keep up with (and contribute to) the tide of celestial novelties revealed by the new viewing tubes were to a large degree dependent on instrument makers for their lenses and telescopes; at the same time, specialized optical instrument makers were increasingly dependent on the savants and elites who purchased their instruments.[25] This interdependence of scholar and craftsman deepened when the project at hand was not simply the making of another tolerable telescope for a wealthy

[23]For material on lens making in the seventeenth century, see Crommelin, *Het Lenzen Slijpen*; Danjon and Couder, *Lunettes et Télescopes*; Daumas, *Les Instruments Scientifiques*, pp. 41–56; De Waard, "Notes sur le Rodage"; and Bedini, "Lens Making for Scientific Instrumentation." Several focused studies are also available, including Bonelli and Van Helden, "Divini and Campani"; and Bryden and Simms, "Spectacles Improved to Perfection." For discussions of microscope lenses (in general made by very different techniques), see Wilson, *Invisible World*, pp. 72–81; Ford, *Single Lens*; and Baker, "Leeuwenhoek, the Short Focus Lens."

[24]For a discussion of the slow movement toward mechanical systems (not significantly changing the character of practice until the mid-eighteenth century at the earliest), see Bryden and Simms, "Spectacles Improved," pp. 6–11.

[25]Ibid., for an excellent treatment of the commercial implications (as well as guild entanglements) of this work.

amateur but the production of a telescope for an astronomer seeking to publish new discoveries. In these cases the relationship between the craftsman and his patron could develop over years and lead to novel collaborations between individuals of substantially different background and expertise.[26]

Before finding a young lapidary and glassworker named Ippolito Francini in the Florentine workshop of the Medici family, Galileo depended on lenses sent from Venice and produced in the way that Della Porta reported that "great lenticulars were made at Venice."[27] In 1623 Galileo began purchasing his lenses from Francini, who probably worked under his personal supervision, preparing components for the most celebrated optical devices in Europe.[28] There is evidence that Francini may have engaged in special lens making projects for Galileo, such as preparing objectives tinted with deep blue lapis lazuli for use in observations of the sun.[29] The excellence of Francini's lenses began a tradition of Italian dominance in the skill of lens craft, and his pride of place passed to Francesco Fontana by the mid-1640s. The skill and renown of Italian lens makers such as Evangelista Torricelli, Eustachio Divini, and Giuseppe Campani assured that Italian lenses were particularly sought after throughout Europe for the duration of the century. The competition between these masters even led to a tradition of public trials known as *paragoni,* in which the telescopes or objective lenses of master craftsmen would be set up beside one another and trained on some distant writing or object, in order to compare clarity and resolving power. These trials could make the career of a young optician just as they could prove a tremendous embarrassment to an established master. Of course, the greatest trials for lenses proved to be whether they were associated with important discoveries in the heavens, for lens makers derived their renown from the successes of the astronomers who used their instruments.[30] In addition to the

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[26]See Van Helden, "Telescope in the Seventeenth Century," p. 49; and Bonelli and Van Helden, "Divini and Campani." Both discuss the risks and benefits of these collaborations. A more general treatment of the circular relationship between the status of observational astronomers and that of their optical craftsmen can be found in Van Helden, "Telescopes and Authority."

[27]See Cohen, "What Galileo Saw," p. 436. Additionally, see Drake, "Galileo's First Telescope"; and Ronchi, *Il cannochiale.*

[28]Through the assistance of Sagredo, many of Galileo's lenses in the first seven years of his residency in Florence came from a mirror maker named Girolamo Bacci (from Murano) and "Maestro" Antonio (of Saint Lorenzo in Frezzaria), as well as a spectacle maker named Armanno. Galileo (like Sagredo) also ground a number of lenses himself, and secured others locally (though without great enthusiasm for the craftsmanship). For a full discussion see Bedini, "Galileo's Scientific Instruments."

[29]Bedini, "Lens Making for Scientific Instrumentation," p. 690.

[30]For a particularly good example of the desire for better lenses to make new discoveries, see the passage from Cozzolani cited by Van Helden in "'Astronomical Telescope'," p. 27.

collaborations between scholars and craftsmen that arose as a result of the telescope, the instrument often bound their fates into one, so that Divini's fall from grace as the most talented lens maker in Italy was occasioned in part by the disproving of the theory of Saturn's form constructed by Honoré Fabri, a Jesuit using one of Divini's instruments.[31]

The only real challenge to the supremacy of Italian lens making in the period came from the Netherlands, where a young Dutch savant named Christiaan Huygens had applied himself to lens making in the 1650s. Christiaan and his brother Constantijn had been raised in a family where artisanal skill was prized alongside scientific learning; their father collaborated with Descartes on his hyperbolic lens grinding machine in the 1630s.[32] When Christiaan published his *Systema Saturnium* in 1659, in which he presented his ring theory to explain the curious appearance of Saturn, he claimed that this astounding new observation was the result of his having learned to make the very best telescopes in Europe. This discovery called into question the supremacy of Divini's lens craft, and it was not until the sensational (and carefully staged) debut of Giuseppe Campani's lenses in 1664 that Italy recaptured the laurel of optical craftsmanship. In a carefully orchestrated *paragone,* Campani's instruments surpassed those of the aging Divini; their respective reputations were adjusted accordingly. It was with the lenses of Campani, carefully carried back from Rome, that Cassini made his celebrated observations of planetary rotation from the Observatoire de Paris. Those now interested in establishing the quality and character of Campani's lenses need not rely merely on tales of the observations made with them: several of his lenses survive. An examination of their resolving power, performed by two historians of science at the turn of the nineteenth century, demonstrated their considerable superiority over the lenses used by Galileo or even those made by Huygens. In fact, one of the examiners argued that a more perfectly formed spherical lens would have been difficult to produce in his own day.[33]

If Campani's lenses thus represented the apex of the seventeenth-century craft of lens making, this brief review of lens making practice

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[31]Bonelli and Van Helden, "Divini and Campani," p. 12.

[32]For a detailed study (using modern optical instruments) of three of Constantijn Huygens' lenses, see Mills and Jones, "Three Lenses." The authors conclude that the lenses were spherically true. See also the pamphlet *The Huygens Collection* by Van Helden and Van Gent.

[33]For an account of these examinations by Klein and Nijland, see Van Helden, "Telescope in the Seventeenth Century," p. 46, n. 38. Campani's lenses were demonstrated to approach more closely the "predicted theoretical resolution" for their aperture than did Huygens'.

in the period should close with an examination of how Campani made his lenses. Unfortunately, this has remained a story shrouded by the master's own reticence (and even dissimulation). In the competitive world of craft rivalries and courtly patronage, where the first best instrument allowed for novel discoveries and the rest served merely to review familiar celestial ground (or confirm the fêted novelties of others), much could be gained by a choice whisper (true or false) or a corresponding silence.[34] Campani ranked as a master here as well: he jealously guarded his techniques as trade secrets and taught no one but his only daughter, who never made her father's methods public.[35] Pope Benedict XIV acquired the contents of the Campani workshop in 1747 and the instruments came under the scrutiny of an emissary from the Académie Royale des Sciences in 1766.[36] The report that was read to the Académie survives and offers some clues about what could be gleaned from the inspection of Campani's studio, now long since dispersed. Campani ground his lenses in metal forms, just as Francini and others did before him. The excellence of his lenses can in part be ascribed to his use of a form of lathe with a pivoting radial arm, which he used to help shape the metal forming pans.[37] Given, however, that this kind of lathe was widely known at the time, this alone cannot account for the supremacy of Campani's optical craftsmanship.[38] Subtle craftsmanship—like the careful examination of glass blanks under strong light using a concave mirror, and the

[34]On the culture of scientific craftsmen in court contexts, see Moran, *Patronage and Institutions*. For an excellent example of the intrigue that attended this work, note that Torricelli went to his (untimely) grave only after having arranged for the details of his lens making technique to be secreted in a sealed coffer and hustled to the protection of the Duke of Tuscany by a trusted friend at four o'clock in the morning. (De Waard, "Notes sur le Rodage," p. xii, n. 1.) See also Biagioli, "Replication or Monopoly?"

[35]For a discussion of Campani's tools, see Bedini, "Optical Workshop." In 1962 Bedini put forward an anonymous manuscript discovered in the Biblioteca Universitaria of Bologna as (probably) the work of Campani himself. I am unaware of any refutations of this identification, but think it best viewed as optimistic. See Bedini, "Making Telescope Tubes."

[36]Bondaroy, "Mémoire."

[37]A lathe he claimed allowed him to cut lenses of all shapes (not necessarily limited to spherical); see Hashimoto, "Huygens, Dioptrics," p. 76.

[38]Galileo refers to employing a lathe in the grinding of an (unsuccessful) lens in 1618. See Favaro, *Le opere di Galileo*, Vol. 12, p. 418. The earliest published handbook on telescope making (Sirtori's 1618 *Telescopium*) mentions the lathe as a tool for making forms (p. 34), and images of the form-shaping lathe as well as several configurations of form-spinning lathes (for assisting in the grinding of the glass itself) can be found in Manzini's 1660 *L'Occhiale all'Occhio* (pp. 158, 162, 223) and in Maignan's 1648 *Perspectiva Horaria* (propositions 70 and 71). For a discussion of the form lathe of Hevelius (which included a ratcheted barrel to prevent the counter-rotating motion of most pedal-driven lathes), see Winkler and Van Helden, "Johannes Hevelius," pp. 102–3. Campani's (secretive) lens lathe became the focal point for a widespread rumor that lenses could be cut directly on the lathe, without the intervening step of shaping a metal form or pan in which the glass was turned and ground. Discussions of such systems circulated throughout the century, though there seems to be no proof that any was realized for use on large, objective lenses of the highest quality. For a discussion rejecting Campani's claim, see Grillot, "L'Emploi des Objectifs," particularly pp. 149–50. For an example of an elliptical reference to the process from the mid-seventeenth century, see Bedini and Bennett, " 'Treatise on Optics'," particularly pp. 115–16. Cherubin D'Orleans took the subject up at the end of the century (see chapter 3). For a useful discussion of the lathe and its (vaunted) status in the seventeenth century as an instrument for making wonders and occupying noble leisure, see Connors, "*Ars Tornandi*."

patient grading of abrasives and polishes—almost certainly characterized Campani's shop practice.

Campani's lenses achieved a degree of perfection quite close to the limits of what was possible using available technology and working within the boundaries of seventeenth-century optical theory. The visual images provided by his instruments proved superior to those of other telescope makers, but they were not perfect. From the first, telescope fields had been distorted and obscured by colored fringes that surrounded images like halos. The theoretical optics of Kepler laid the groundwork for an interpretation of this phenomenon in 1604. Later, in 1637, Descartes provided the explanation that would endure until Newton's discovery of the composite nature of light in the late 1660s.

Descartes' explanation for this spectral distortion traced its way back to a problem found in the work of Archimedes: the problem of the anaclastic. The solution to the anaclastic involves determining the shape of the curved surface necessary to refract (or reflect) a set of parallel rays to a single point. The mythic parabolic burning mirrors erected under the supervision of Archimedes to defend the city of Syracuse from besieging navies represented the archetypal solution to the anaclastic for reflection.[39] The only principle of physical optics needed to solve the anaclastic for reflection was the fairly intuitive law of reflection: the angle of incidence equals the angle of reflection. Solving the anaclastic for refraction proved much more difficult, but was understood even at the end of the sixteenth century to be central to the study of lenses. Della Porta knew that the most powerful burning glass would be the one uniting the most rays at the narrowest point, and though he provided no theoretical justification, he argued—by analogy to the parabolic burning mirror—that a parabolic lens would solve the problem.

Kepler approached the problem theoretically (using a table of refraction borrowed from the medieval optical tradition of Witelo), and settled on the hyperbola as the solution, though he was dissatisfied with the rigor of his demonstration. His arguments depended on rhetoric and analogy, including an assertion that a cross section of the lens in the eye of a cow looked like a hyperbola. His attempted proofs failed, and he made no effort to conceal his irritation:

> Almighty God! How much time have I wasted by my faith in AL-GEBRA! I include here an outline of my proof for those who might take pleasure in crucifying themselves upon it.[40]

[39]The incident became iconic for optical craftsmen, intimating their noble forebears and potent abilities. For an overview, see Simms, "Archimedes and the Burning Mirrors."

[40]I have used a 1968 facsimile edition of Kepler's 1604 text (for a full citation, see the bibliography): Kepler, *Ad Vitellionem Paralipomena*, p. 107. Note that Kepler "personifies" algebra, with an allusion to an Islamic sage. For a discussion, see the annotations in Kepler, *Paralipomènes à Vitellion*, p. 458.

Descartes called Kepler "my first instructor in optics" and may have become interested in the problem of the anaclastic through a reading of the *Ad Vitellionem Paralipomena*.[41] When Descartes attacked the problem in the middle of the 1620s, he had a powerful tool: a reliable formulation of the principle of refraction, known now as Snell's law.[42] Using this generalized mathematical statement of the physical phenomena of refraction, Descartes was able to corroborate Kepler's suspicion by means of an elegant proof, which he presented to his friend Claude Mydorge sometime before 1626. In that year the proof appeared in a letter from Mydorge to Mersenne.

The stakes at play in a solution to the anaclastic for refraction had risen dramatically between 1604, when Kepler first played with the problem, and 1626, when Descartes revealed his solution. For although Kepler had understood that the solution to the anaclastic would indicate the ideal shape for "enlarging lenses," the invention of the astronomical telescope had propelled the anaclastic to the forefront of concern in the new sciences. The rays of light reaching earth from a celestial body (assumed to be infinitely distant) could be considered parallel, making the problem of effectively focusing the rays in a telescope a direct application of the anaclastic. There can be no doubt that Descartes quickly realized the implication of his proof for telescopes, for between 1626 and 1629, when he left for Amsterdam, he was already engaged with Mydorge and Ferrier in the grinding of hyperbolic telescope lenses.[43] By the time Descartes published his exhaustive treatment of the anaclastic and its application to optical devices in both *La Dioptrique* and *La Géométrie* of 1637, the stakes had been raised yet again, owing to the increasing popularity of "flea glasses" among virtuosi across Europe.[44] In a microscope, the light coming from the object could be idealized as originating from a point source at a finite focal distance. Once again, the curve needed to produce a magnified image with minimum distortion would be the

[41]See Simon, "Theory of Visual Perception."

[42]Descartes' path to the law of refraction has been the subject of a number of studies. For the most recent (brief) summary of the several competing accounts, see Gaukroger, *Intellectual Biography*, pp. 139–46. Treatments of the route to the discovery per se include Schuster, "Scientific Revolution," pp. 299–328; and Shea, *Magic of Numbers*. Other studies of the background and context include Eastwood, "Descartes on Refraction"; Sabra, *Theories of Light*, pp. 93–135; Smith, "Light and Refraction," pp. vii, 1–92.

[43]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 13. Note that (as in other things) Descartes' original inspiration appears to have come from Beeckman, who was experimenting with lenses based on conic sections in the early twenties; see De Waard's "Notes sur le Rodage," p. vi.

[44]Hall, *Revolution in Science*, p. 252.

anaclastic curve, in this case flipped over from the orientation used in the telescope.

The rigorous proof of the hyperbolic solution to the problem of the anaclastic for refraction carried with it a striking implication: the spherical lens was not the ideal form for optical instrumentation.[45] Even a perfectly formed spherical lens would still present an imperfect image, owing to the smearing of the focal point along the axis of the lens, what came to be called "spherical aberration" (Figure 1). With this understood, craftsmen and observational astronomers alike began to ascribe the shortcomings of their lenses—blur, color fringes, distortions—to their sphericity.[46] In fact, the color fringes that constituted the salient obstruction to clear viewing were unrelated to spherical aberration and resulted from chromatic aberration, the product of the differential refraction of different wavelengths of light.[47] Not until Newton's investigations of the nature of color in the late 1660s (which resulted in part from his foray into lens grinding) did the possibility of chromatic aberration arise, at which point another fundamental limitation on the potential of the uncorrected glass lens was revealed.[48]

From the late 1620s to the early 1670s, then, spherical aberration was thought to be the only limitation on the power of lenses, besides

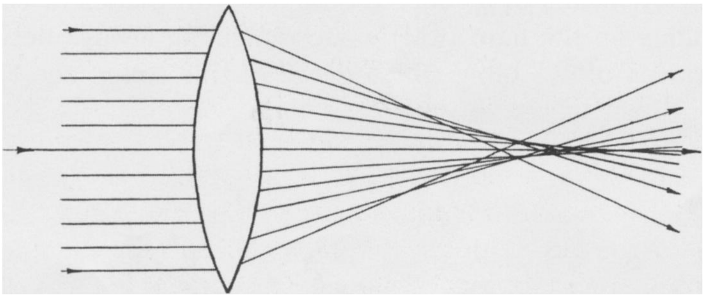

Figure 1 Spherical aberration

[45]I refer to the "hyperbolic solution," though Descartes recognized two possible lens shapes that promised optical perfection: plano-hyperbolic and ellipso-spherical (see book viii of *La Dioptrique*, in Adam and Tannery, *Oeuvres de Descartes,* Vol. 6, pp. 165–96). My focus on the plano-hyperbolic follows Descartes, who considered it superior (for its simpler form and manufacture) than the ellipso-spherical.

[46]Examples of the attribution of color fringes and distortion to spherical aberration can be found in De Waard, *Journal tenu*, Vol. 3, p. 234; and Shapiro, *Optical Papers*, Vol. 1, pp. 46, 47.

[47]For a modern examination of a contemporary instrument that reaches the conclusion that performance was limited by chromatic aberration, see Miniati et al., "Examination of an Antique Telescope."

[48]*Philosophical Transactions of the Royal Society* 5, no. 80 (1671): 3075–87.

the craft limitations of lens makers. Descartes believed that he could overcome both of these difficulties with the design of a fully automated lens making system that would produce hyperbolic lenses. His machine was designed to solve the complex geometrical problem of the anaclastic in glass, while eliminating the irregularities he believed were introduced by handcraft. While the system underwent a number of revisions, Figure 2 represents the design best known in the seventeenth century, as it was this engraving that terminated *La Dioptrique* and that Descartes challenged his readers to realize in 1637.

Most of chapter 2 will be concerned with this device and the details of its (imagined) operations, but the following is a compressed account of its workings for readers who wish to take a moment now to familiarize themselves with the technical features of the process Descartes envisioned: Truss BKA (which extends down to M) swings from two pivot points at 2 and 4, and thus moved, its lower limb (KM) evolves a cone, the apex of which lies at 3. Because this movable limb (KM) passes through the double-surfaced table FE, the intersection of the plane defined by the tabletop with the path of the limb (KM) traces a hyperbola (because a hyperbola is the conic section produced by cutting a cone parallel to its axis). The line of this hyperbola is transferred to both a grinding wheel (at left) and a set of metal plates (at right) by means of a roller (equipped with blades at each end), which slides on the limb (KM) while remaining always between the twin surfaces of the table (for a detail of this roller, see Figure 14,

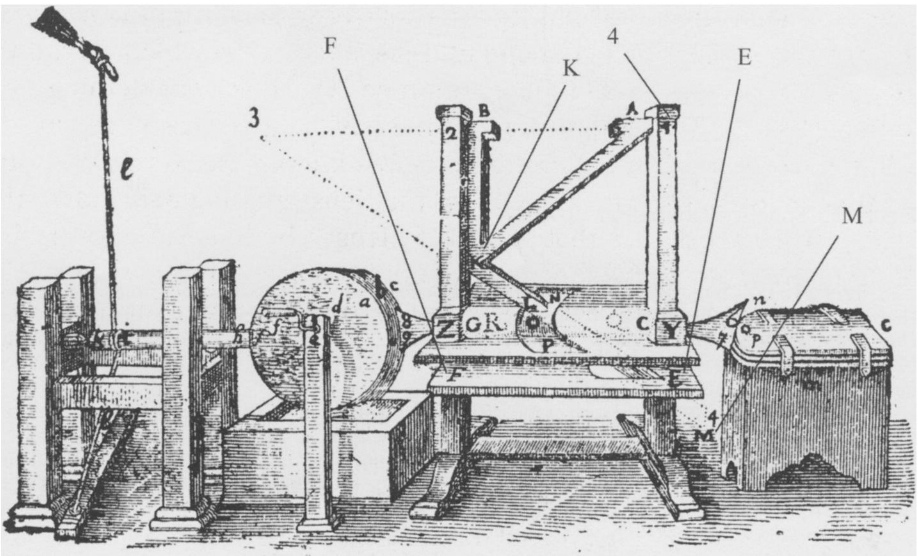

Figure 2 Descartes' machine (Adam and Tannery, *Oeuvres de Descartes*, Vol. IV, p. 218)

p. 46). A hyperbolic lens is formed by pressing a piece of glass, spinning on a lathe (at the extreme left in the image), into the hyperbolically grooved edge of the grinding wheel. The trimmed plates serve as a gauge for the wheel and the lens, to assure that their form is true.

THE CONTEXT FOR THE CARTESIAN MACHINE

Several observations stand to be made about this apparatus and its representation.[49] First, a close examination of Figure 2 reveals Descartes' preoccupation with the automation of his device. The illustration systematically omits references to the craftsmen who would presumably operate the system: the crank on the grinding wheel (the only visual allusion to the machine's need for human attendance) is tiny and obscured; there is no indication of the need for a craftsman to advance the lens blank onto the turning grinding wheel; there is no evidence that the truss BKA will need to be swung from side to side, because handles for this process have been overlooked, and there is no space for a worker to stand in order to perform this task.[50] Unlike the tradition of mechanical illustration rooted in the late Renaissance theater of machines—where mechanical devices were literally "staged" in scenes and depicted in use, attended by their operators—Descartes' machine stands alone.[51] It is represented as essentially independent, more or less autonomous, and seemingly capable of shaping lenses with (at best) a minimal degree of human engagement.

The illustration of the machine communicated (by commission and omission) that lens making artisans were not central to its operation. This confirms the conceptual framework out of which, I want to argue, the design for the machine arose. There is considerable evidence that Descartes conceived of the hand of the artisan as, above all, a source of error, and believed it was impossible to rely on craft practices for the levels of accuracy that lens grinding demanded. He wrote in *La Dioptrique* that "polishing lenses by hand in a form, the only method which has been in use until the present, it is impossible to make anything good except by chance, even when the forming pans are perfect."[52] This amounted to an (unsubstantiated) indictment of the

[49]For a useful discussion of the techniques and traditions at play in the visual representation of mechanical devices in the early modern period, see Lefèvre, *Picturing Machines*.

[50]For a discussion of Descartes' use of illustration (and his close oversight of their engraving), see Baigrie, "Descartes's Scientific Illustrations." See also Grosholz, "Geometry, Time and Force"; and Blakemore, "Understanding Images," pp. 257–61.

[51]The reader of *La Dioptrique* finds there no "narrative of assimilation" for the machine, either in the images or in the text. See Knoespel, "Gazing on Technology."

[52]Adam and Tannery, *Oeuvres de Descartes*, Vol. 6, p. 224.

very craft practice that had accounted for all astronomical discoveries made up to that point (as well those made in the remainder of the century). Significantly, it was an accusation repeated by various savants throughout the century. Like them, Descartes perceived the hand of the craftsman as an unfortunate and unreliable element of lens craft. In response to the suggestion that medium-sized hyperbolic lenses could be ground by hand in a pan, he wrote a young mathematician and craftsman in 1638: "I do not know that one can, turning the glass with the hand, assure that it retains always the same motion, and even if it should vary a little bit, that will prevent the shape from being correct."[53] He then went on to describe a geared device designed to steer the glass in the form.

Descartes' desire to replace (to whatever degree possible) the hand of the craftsman with the arms and wheels of mechanical systems for lens making represents a significant extension (and transformation) of Renaissance traditions of machining and instrumentation. It is to these traditions, and their relationship to Descartes' machine, that I turn in the three sections to follow. The first looks at the tradition of lathe craft in the sixteenth century, with an emphasis on systems designed to make complex forms by guiding the free hand of the artisan. The second suggests the importance of mathematical instruments as mechanical systems for generating complex curves. In the third section, I turn to the broader context of the mechanical philosophy, in order to show how the idea of automating the making of a complex artifact can be related to a more general interest in automatons, as well as to a particular concept of machines and their place in the world (and in the mind).

Ars Tornandi

The European fascination with lathes and their productions from the Renaissance through the baroque period has been well documented.[54] In particular, the ambivalent social status of the art of turning—a suitable occupation for the noble leisure of princes and their circles, the craft of petty tradesmen—has become increasingly clear. The remarkable achievements of turners who created intricate objects for inclusion in what became the celebrated Renaissance inner sanctum of wonder, the *Kunstkammer*, are of central interest in establishing the provenance of Descartes' ideas about the role of a lathelike system for precision making. Concentric spheres featuring elaborate openwork (*Contrefaitkugel*), ivory and ebony urns, and fragile helical towers

[53]Ibid., Vol. 2, p. 454.
[54]For an introduction to the history of the lathe, see Woodbury, *History of the Lathe*. For more recent essays, see Gambaruto, "Il Tornio"; and Connors, "*Ars Tornandi*."

all emerged out of the patient labor of the dedicated craftsman and his lathe. Moreover, these curiosities were not merely additions to the cabinet of wonders, but in a sense lay at its heart: one account of the origin of the *Kunstkammer* traces its courtly genealogy back to the workshop of the turner who served the king.[55] No better example can be offered of the way the lathe and its artifacts occupied the same architectural and conceptual space as the investigations of optics and instrumentation than that afforded by the career of Manfredo Settala, who "[i]n his laboratory near S. Nazzaro . . . ground burning mirrors, made watches and precision instruments, and turned ivory on the lathe"; it was with a sample of this last artistry that Settala chose to be memorialized in his portrait.[56]

Descartes was certainly acquainted with the products of lathes like those of Settala, just as he was familiar with the cruder lathelike grinding systems used by the makers of arms, armor, and cutlery (and depicted in a number of different forms in Vittorio Zonca's *Novo Theatro di Machine et Edificii*; Figures 3 and 4).[57] More important, he was familiar with at least one book that discussed the making of such lathes, *Les Raisons des Forces Mouvants avec Diverses Machines*, authored by Salomon de Caus, a French engineer serving in the court of the Palatine Elector.[58] This text of 1615 presents a detailed illustration of a lathe, a turner, and his workshop (Figure 5).[59] De Caus' lathe, however, was no ordinary turning tool; in fact, it represented a sophisticated modification of basic turning techniques, in that it was an *eccentric* lathe, equipped to turn noncylindrical and nonspherical forms: ellipsoidal cams fixed to the main axis impart to the work an ellipsoidal rotation, allowing the artisan to form vases and cups of a variety of unusual shapes.

Such lathes can be traced back at least to 1578, when illustrations of several of them appear in Jacques Besson's *Theatrum Instrumentorum et Machinarum,* from which de Caus may have copied (Figures 6 and 7).[60] Besson not only showed the use of eccentric lathes, but also demonstrated that the concept of constraining the free hand

[55]Gudestrup, "Royal *Kunstkammer.*" A similar point is made in more general terms by Bredekamp in his *Lure of Antiquity*, p. 39.

[56]Connors, "*Ars Tornandi,*" p. 221.

[57]Recall Descartes' military sojourns. The grinding wheels of Zonca are depicted on pp. 33–41 ("Mola d'aguzzar, incavar et brunir á mano") of the 1607 book, which has been republished under the editorship of Carlo Poni: Zonca, *Novo Theatro.*

[58]de Caus, *Les Raisons des Forces Mouvantes*. Gaukroger (*Intellectual Biography*, p. 427, n. 61) asserts Descartes knew the text. For a discussion of Descartes' description of several automatic devices matching those of de Caus, see Shea, *Magic of Numbers*, pp. 182–4. It is possible Descartes had seen the devices themselves in the royal gardens at Saint-Germain-en-Laye, though this can not be established definitively (Gaukroger, *Intellectual Biography*, p. 64).

[59]See problem 21, plate 28.

[60]I have consulted the 1578 French edition in Avery Library, Columbia University: Besson, *Théâtre des Instrumens*. The lathes appear in plates 7–10.

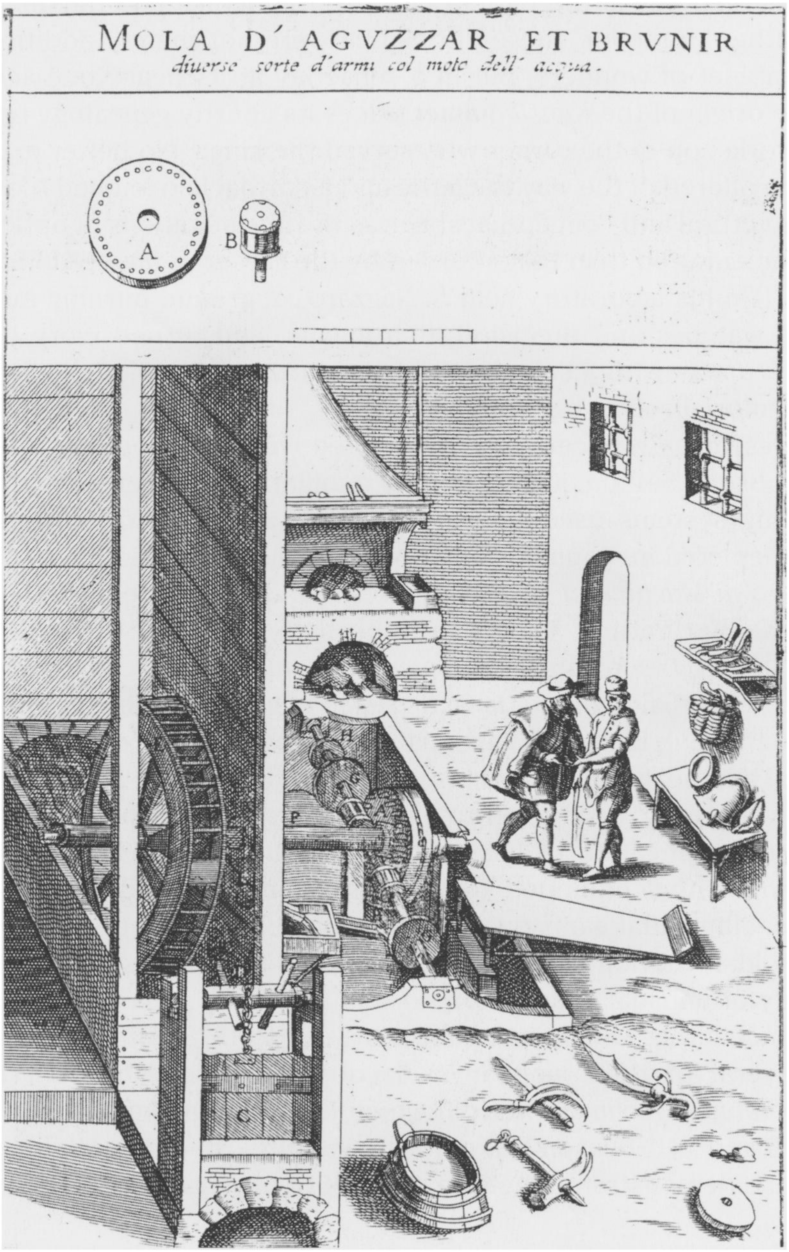

Figure 3 Zonca's grinding wheel (Zonca, *Novo Theatro di Machine et Edificii*, p. 39)

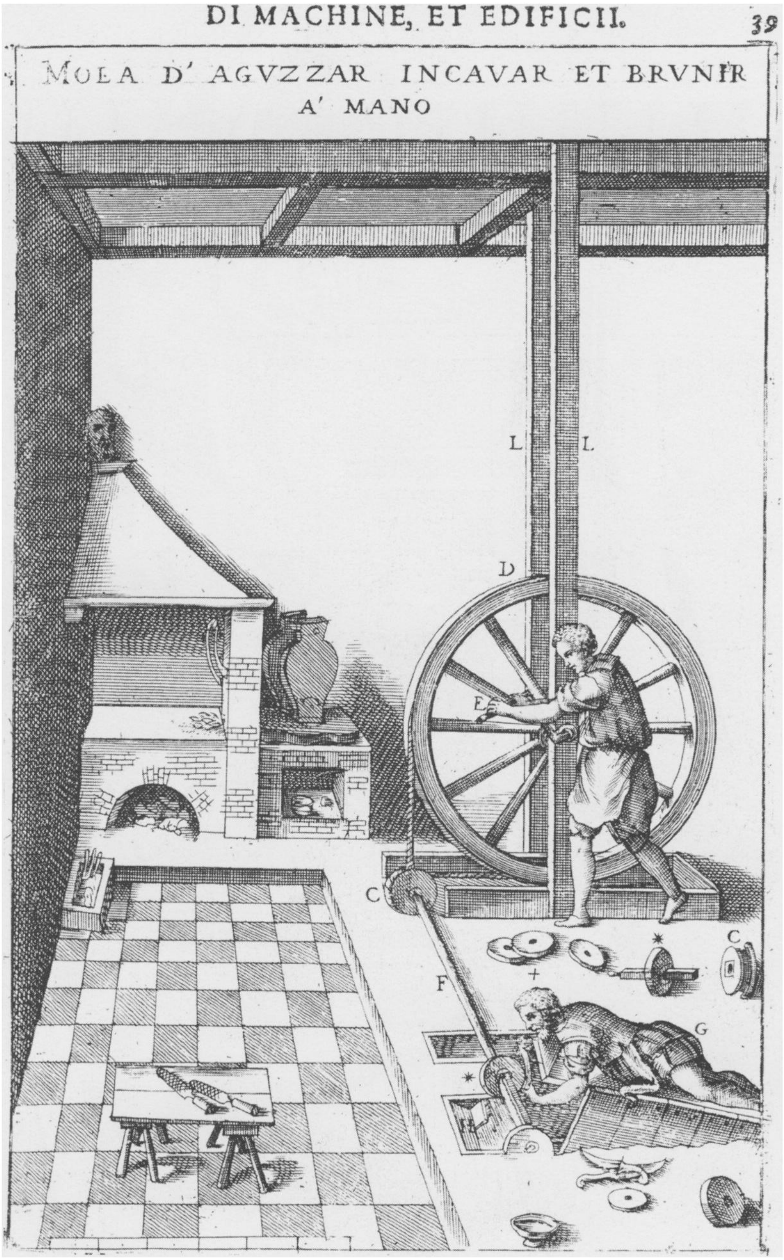

Figure 4 Another Zonca grinding wheel (Zonca, *Novo Theatro di Machine et Edificii,* p. 36)

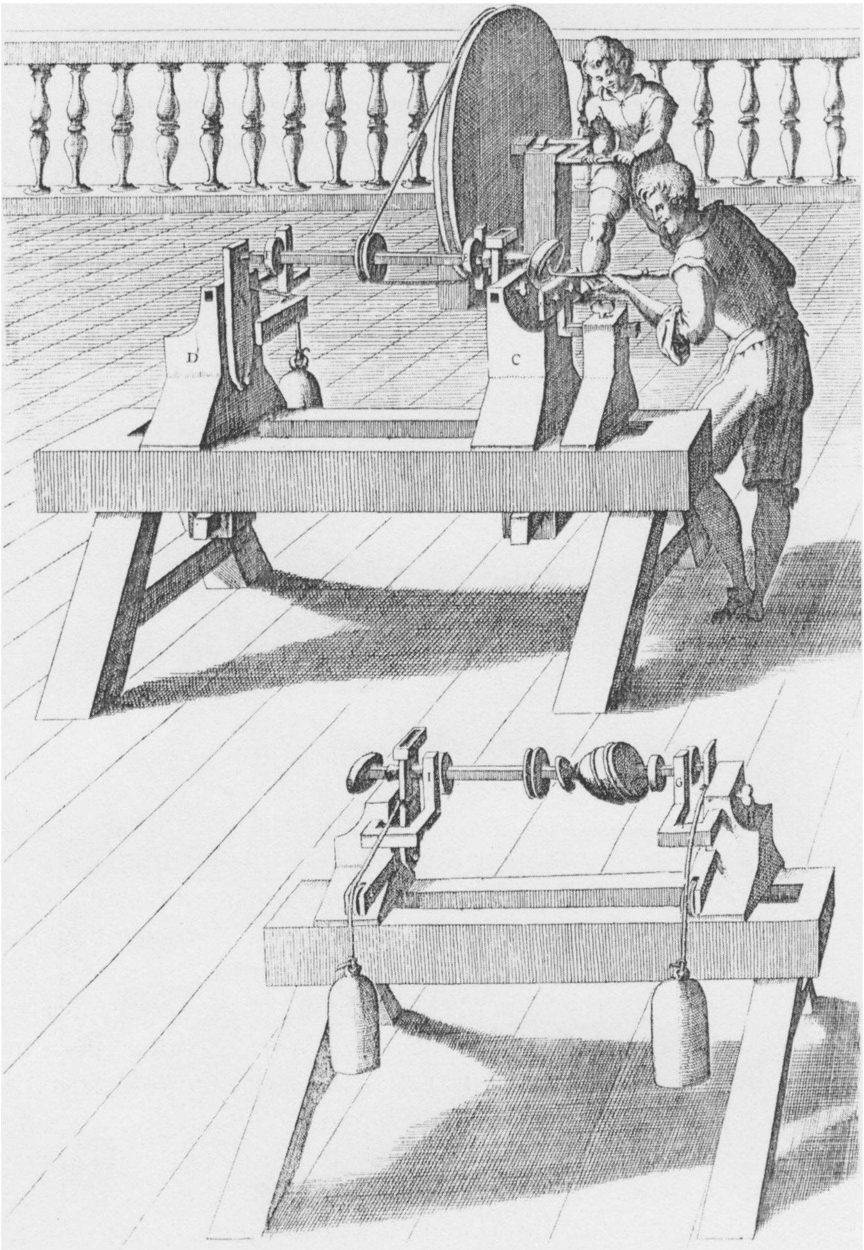

Figure 5 De Caus' lathe (Caus, *Les Raisons des Forces Mouvantes*, p. 28)

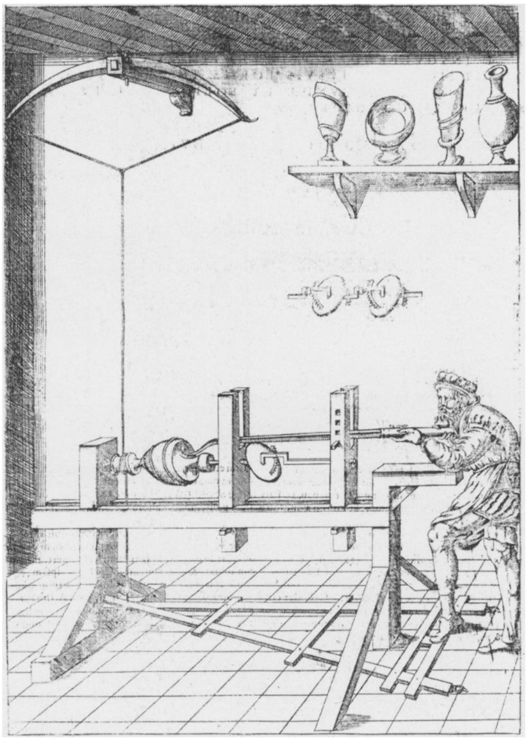

Figure 6 Besson's end lathe (Besson, *Théâtre des Instrumens*, plate 8)

of the artisan in the sculpting process did not originate with Descartes: Besson depicted an attachment that allowed a lazy strut to ride on the cams of the main axis; a template cut into the strut permitted the tool of the artisan to be guided along a path (Figure 7). Such templates, held next to the work as gauges, can be presumed to have been part of shop practice from the time of the Romans, but the incorporation of these guides into the lathe itself represents a significant step toward the realization of self-regulating tools for fine manufacture. This process advanced despite the continued appeals (among literate ornamental turners throughout the century) to the superior beauty of the work of the free-handed turner at the lathe.[61] The most dramatic instance of the mechanizing tendency in Besson's work lies in his depiction of a screw-cutting lathe in plate nine of the *Theatrum Instrumentorum et Machinarum* (here shown as Figure 8). In this design a "master screw" advances a cutting tool, which in turn cuts threads

[61]For more on the history of regulating systems for mechanical tools, see Woodbury, *Studies in the History*; and Rolt, *Tools for the Job*. For Plumier's "genius of the free hand" (in his 1701 *L'Art de Tourner*), see Connors, "*Ars Tornandi*," pp. 226–7.

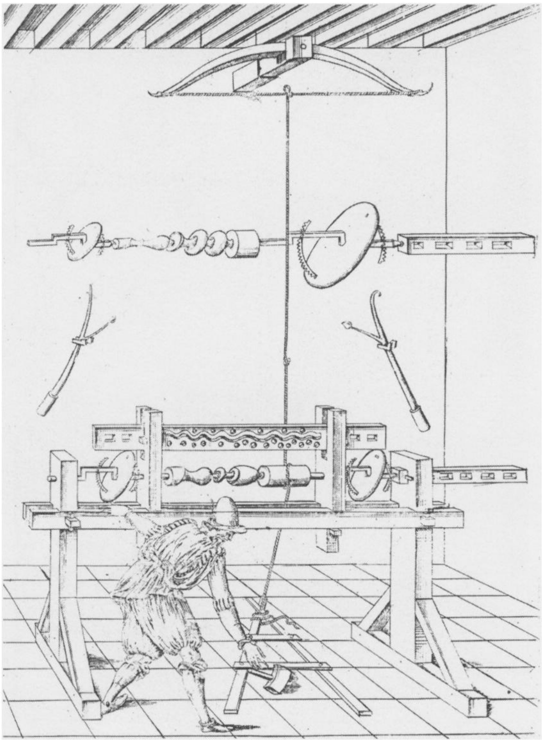

Figure 7 Besson's lathe with a lazy strut (Besson, *Théâtre des Instrumens,* plate 7)

on the "blank" tapered shaft (at left). Although Besson's devices, situated in a speculative and dramatic mechanical compendium like that of Ramelli or Böckler, have not infrequently been considered fanciful, excellent evidence exists that such lathes came into use at least a century before.[62] The currency of such mechanical modifications of the lathe—noncircular rotations for cutting aspherical forms, templates and automated cutting attachments for guiding the work—suggest an expanding range of applications for the device, and offer a sense of lathe systems that can be expected to have been familiar to Descartes and those working with him.[63]

Ars Mathematica

Most often cited as an example of the late Renaissance corpus of books on fortifications, mining, and siege machines, Besson's work

[62]Ramelli's 1588 text, *Le Diverse et Artificiose Machine*, is available in a reprinted edition, Gnudi, *Various Ingenious Machines*; Böckler's *Theatrum Machinarum Novum* was published in 1661; Battison, "Screw-Cutting"; see also Brooks, "Perfect Screw Thread."

[63]"By reason of the fame of the work in which it appeared, Besson's lathe is a very likely candidate for spreading the idea of mechanical tool control widely among European craftsmen and intelligentsia," Foley et al., "Early Slide-Rest," p. 56.

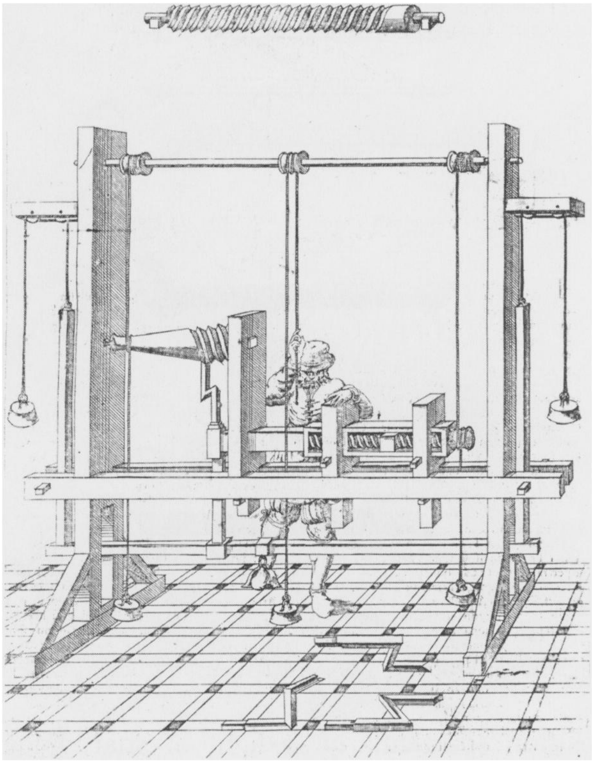

Figure 8 Besson's screw-cutting lathe (Besson, *Théâtre des Instrumens,* plate 9)

rightly belongs on the margins of a distinct but related enterprise as well: that of mathematical instrument making.[64] His title (*Theatrum Instrumentorum*) immediately suggests the importance of this other mechanical project, concerned not with man-sized (and larger) devices for augmenting human power and reach, but rather with hand-sized devices for measuring, drafting, and calculation. Of the first six devices depicted by Besson, five of them fit squarely within this tradition: a proportional compass; three drafting tools for drawing different circular or oval *fleurs* of varying degrees of complexity; and a screw-driven instrument that, when fixed to a drawing-board and spun, traced out a spiral whorl (Figure 9). Despite (or perhaps because of) the puzzling underlying geometry of several of these devices, Besson chose to give them pride of place in his volume, immediately preceding his lathes.

[64]A number of works clarify this tradition and its significance. See, for instance, Turner, "Paper, Print and Mathematics"; idem, "Mathematical Instruments"; Bennett, "Challenge of Practical Mathematics"; and Johnston, "Mathematical Practitioners." The classic studies remain: Taylor, *Mathematical Practitioners of Tudor and Stuart England*; and Daumas, *Les Instruments Scientifiques*. Also of interest is Clifton and Turner, *British Scientific Instrument Makers*.

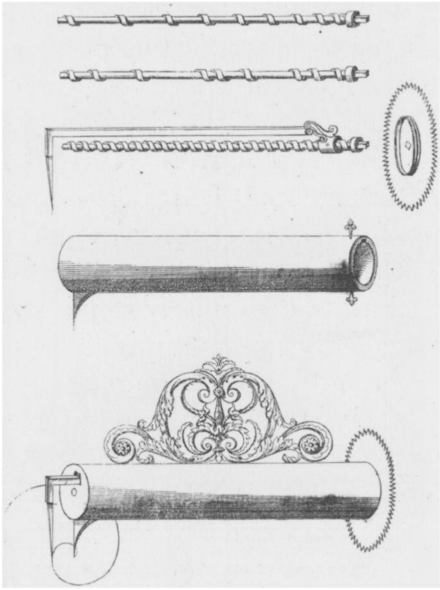

Figure 9 Besson's spiral device (Besson, *Théâtre des Instrumens,* plate 6)

This juxtaposition (particularly in light of shared features of the devices, namely threaded drive screws) points to the conceptual proximity of mathematical instrumentation and mechanical turning systems.

Still more striking evidence for this close relationship has been provided by a recent meticulous reconstruction of the workings of a screw-cutting lathe akin to that of Besson.[65] In an effort to understand the practical utility of mechanical cutting tools used for threading breech plugs on firearms in the fifteenth and sixteenth centuries, the authors of this study executed a full-scale prototype of one of these devices and used it to cut several conical plugs. Their report of this endeavor reveals an interesting observation: although these mechanical tools look as if they were constructed to cut threads mechanically, they were almost certainly incapable of such heavy work; rather, the authors conclude, the devices must be thought of as "layout tools," which served to score a helical guideline on the cone (or cylinder), a mark that then served as an index for hand cutting by file.[66] Their

[65]Foley et al., "Early Slide-Rest."

[66]Ibid., p. 38. Bedini discusses Galileo's interest in similar screw-cutting tools. See Bedini, "Galileo's Scientific Instruments," pp. 91–92.

conclusion—that the role of such machines was "chiefly geometrical"—signals the close proximity between mathematical instruments and mechanical systems for manipulating piecework on the lathe.

Given the complexity of the curve necessary to thread a cone, mechanical guides (coupled with the practice of skewing the axis of the work with respect to the cutting head) became useful supplements to hand-and-eye craftsmanship. Driving this process in part was a still more complex machining problem with its origins in the mid-sixteenth century: the fusee. The application of spring drives to clockworks (circa 1430) vastly expanded the range of styles, sizes, and mechanical configurations for timepieces, precipitating considerable experimentation with novel drives and works in increasingly portable devices. Much of this was directed at the search for reliable systems to offset the changes in clock speed occasioned by the decreasing motive force of an unwinding mainspring. The basic solution to this problem remained fundamental to clock design for half a millennium: driving the main gear of the works by means of a chain that spooled off a conical drum (the fusee) driven directly by the spring.[67] This arrangement used the principle of increasing mechanical advantage to compensate for the progressively weakening power of the mainspring. The trial and error pursuit of the even, constant power necessary to accurate timekeeping led early to the realization that the ideal shape for a fusee was not, in fact, a simple cone, but rather a curved one, the form of which proves to be a hyperboloid.[68] Such devices were a universal feature of spring-driven clocks in the late sixteenth and early seventeenth century, and therefore they appeared not infrequently in clockwork automata of the kind that so fascinated Descartes.[69] Although a handcraft technique for the shaping and fine-tuning of (hyperboloid) fusees can be reconstructed, the complexity of their form gave rise to a number of attempts to codify their geometry into the mechanics of a slide-rest fixed to a lathelike engine.[70] In sum, in this important late sixteenth- and early seventeenth-century domain,

[67]Discussed by Landes, *Revolution in Time*, pp. 86–87, 98. I have also consulted Bruton, *Clocks and Watches*.

[68]Of one sheet. For a full discussion see Honig, "Analysis of the Fusee." Note that no simply conical fusees survive; Honig (very plausibly) hypothesizes their having existed, and having served as the first attempts to correct the mainspring's diminishing force.

[69]For an example (c. 1630), see illustration of "Table carriage with Minerva," item 108 in Maurice and Mayr, *Clockwork Universe*, pp. 282–83.

[70]For the handcraft technique, see Honig, "Analysis of the Fusee," p. 115. It involved the application of an "adjusting rod" to the cone in order to observe the torque it created, followed by corrective filing and the repetition of the process. On the early slide-rest, see Woodbury, *History of the Lathe*, pp. 65–67.

mathematical instrument making—particularly those aspects of it devoted to the production of geometrical tools for drafting and scribing—intersected with traditions of precision lathe-craft and mechanically aided manufacture.

Against this background, a discussion of Descartes' own exploration of mathematical instrumentation provides insights into his thinking about mechanical systems and their relationship to geometry. Descartes' interest in such instruments can be traced to his early investigations (with Beeckman) of proportional compasses in the period 1618–1619, work that can be understood as emerging out of an instrumental tradition established by the devices of Levinus Hulsius and Guidobaldo del Monte, which had received increasing attention in the early seventeenth century as a result of the publications of Galileo and Johann Faulhaber (with whom Descartes appears to have been acquainted).[71] This work led (though in a manner not entirely clear) to the two mathematical instruments presented in *La Dioptrique* and (at least in part) to Descartes' radical rethinking of the relationship between number and spatial considerations.[72] Faced with the problem of defining curves acceptable in geometry, Descartes made considerable inroads against a cardinal principle of classical geometry by countenancing mechanical constructions of "geometrical" curves. In general, Greek geometers considered properly geometrical curves (those fundamental to an established repertoire of proofs in geometry) and mechanical curves (those necessitating the assistance of some mechanical device in order to be drawn and demonstrated) to belong to mutually exclusive categories.[73] Descartes rejected this distinction, and went on to use a mechanical conceit in his definition of the geometrical curve:

> It seems very clear to me that if (as is customary) we consider geometrical that which is precise and exact, and mechanical that which is not, and if we consider geometry as the science that furnishes a

[71]On Descartes' early interest, see Gaukroger, *Intellectual Biography*, p. 69. For an excellent treatment of such devices, see Drake's introduction in Galileo, *Geometric and Military Compass*. For Descartes and Faulhaber, see Shea, *Magic of Numbers*, pp. 103–7. Faulhaber's relationship to craftsmen (and his appropriations from their domain) has been treated in Schneider's *Johannes Faulhaber*.

[72]Given the important place of this work in the history of algebraic thought, it has been the subject of considerable attention. Introductions to this literature can be found in the following recent treatments: Gaukroger, *Intellectual Biography*, pp. 89–103; and Shea, *Magic of Numbers*, pp. 35–68. Valuable studies include Molland, "Shifting the Foundations"; Schuster, "Scientific Revolution," pp. 111–47; idem, "*Mathesis Universalis*," pp. 41–96; Bos, "Curves in Descartes' *Géométrie*"; Grosholz, *Cartesian Method*, pp. 38–60; and Gaukroger, "Nature of Abstract Reasoning."

[73]Exceptions might include Diocles or Anthemius of Tralles. My thanks to an anonymous referee for refining my claims about Greek conceptions of ideal curves.

> general knowledge of the measures of all bodies, we have no more right to exclude the more composite lines than the simpler ones, provided that *one can imagine them as described by a continuous motion or by several motions that follow each other, and of which the last ones are completely regulated by those that precede.*[74]

Unlike the ancients, for whom the suggestion of a mechanical construction raised the specter of dilapidation and inexactitude, Descartes posited a one-to-one correspondence between that of which "one can always have exact measure" and anything generated by the mechanical process he outlined: namely, an order of composite motions, each fully regulated by those preceding. In *La Dioptrique* he provided two diagrams of mechanical instruments that operate according to his exact mechanical outline (Figures 10 and 11). The first device represents a system of linked rods, where XY and YZ are jointed at Y and the shaft BC is fixed to XY at B. The angle-rods CD, EF, and GH are fixed in such a way as to slide along the bar YZ while remaining perpendicular to it (the angle-rods DE and FG work the same way with respect to XY). As XY is scissored opened from YZ, the points B, D, F, and H trace out sequentially higher-order curves. The value of the device lay in its capacity to produce a series of mean proportionals (i.e., YB/YC = YC/YD = YD/YE . . .), the derivation of which

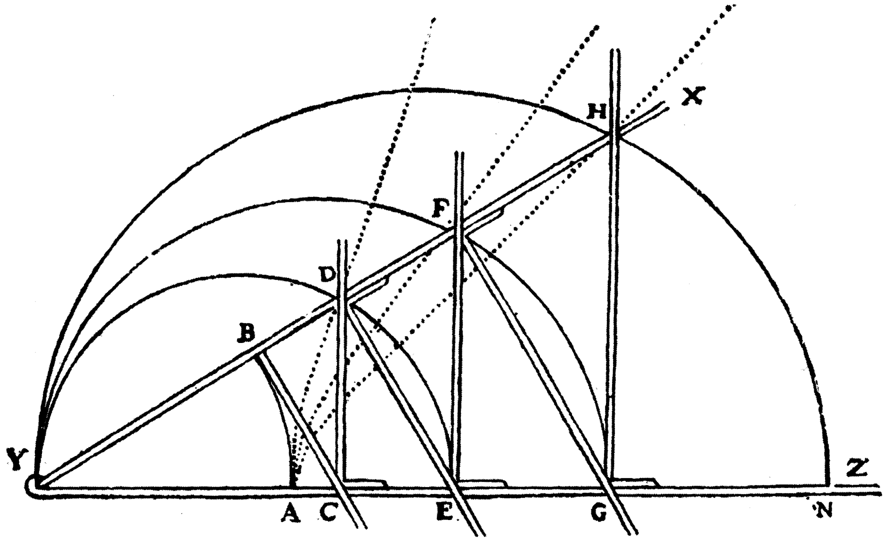

Figure 10 Descartes' mathematical instrument (Adam and Tannery, *Oeuvres de Descartes*, Vol. VI, p. 391)

[74]Adam and Tannery, *Oeuvres de Descartes*, Vol. 6, p. 389 (emphasis added).

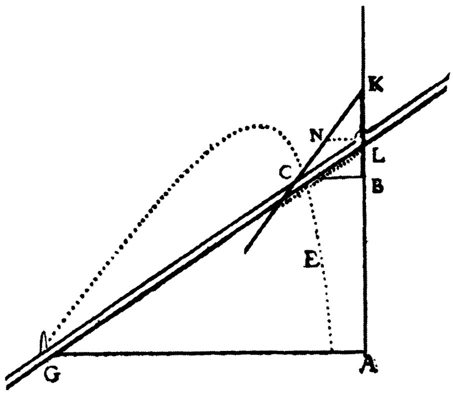

Figure 11 Another Descartes instrument (Adam and Tannery, *Oeuvres de Descartes,* Vol. VI, p. 393)

lay at the center of a number of geometrical problems of legendary difficulty. In the second device, the bar GL pivots at G and slides freely at the point L. The piece BKN slides along the vertical axis, and a curve is traced out at the intersection of the straight edge KN with the bar GL. In this device KN can be replaced with a template curve of any order, and Descartes claimed that the curve traced by the device would be of a higher order than that which served as the template. Both of these devices were presented as infinitely expandable, producing curves of increasing complexity that would never lose their geometrical character.

The role of these devices in stimulating one phase of Descartes' investigation of a *mathesis universalis* has been demonstrated; the precise degree to which they embody his reconception of geometrical problems in algebraic terms (and his abstraction of a concept of number distinct from measure) has been the subject of considerable speculation. What do the instruments and Descartes' conclusions from them indicate about his ideas concerning the relationship between geometry and mechanics? To answer this it helps to consider the distinction between the value of the instruments as heuristics and their value as actual tools for achieving precise pointwise constructions of mean proportionals and the higher-order curves from which they can be derived.[75] In the interest of collapsing the traditional geometrical/ mechanical classification of curves, Descartes pointed out that even circles and straight lines must be drawn by compass or straight edge,

[75]For a valuable look at Descartes' use of illustrative diagrams and their status as instructive/ representational devices, see the two (related) papers by Galison: "Model and Reality"; and "Comparisons."

"mechanisms" of a sort; the distinction between such basic devices and his instruments, as he would have it, is one of degree, not kind. In suggesting as much, Descartes emphasized that the form of a curve can be related to a *conception* of the mechanics of its evolution, regardless of the *actual workings* of the tool involved. In other words, Descartes himself, it seems clear, would have rejected as inexact (and nongeometrical) the *actual* curves drawn by the composite machines that he outlined in *La Géométrie*. In ratcheting up to higher-order curves, the second device is dependent on its own evolutions, which provide templates for each subsequent tracing. Thus it compounds its own error with each iteration, producing curves that would not, in fact, be the result of "exact," "precise," or "continuous" motions. Beyond a few more angle-rods, the precision of the first device would be significantly compromised by similarly compounded irregularities, friction, and general unwieldiness.

The mechanical systems intimated by the drawings in *La Dioptrique* are therefore of primary significance in that they illustrate a kind of mechanized geometry. Descartes never addressed these potential shortcomings of his devices because he did not conceive of them as physical machines but as heuristics, as *ideas of machines*, which served to illustrate the character of regular curves. In fact, Descartes himself stated that the critical component of the mechanical definition of a geometrical curve was not the possibility of building such devices but rather the ability to "*imagine*" them.[76] The definition of the geometrical curve is not based on physical machines at all but on the idea of a machine. To put it another way, the mechanical systems for drawing curves occupy a new place in Descartes' geometry: instead of being merely tools for generating dilapidated appearances of ideal curves, the machine is reconceived precisely as an ideal system that generates our ideas. The concept of a curve, following the concept of the machine, must be incorporated into our minds as a system of relationships between discrete and clearly defined parts.

So deep does the idea of the machine run in Descartes that it becomes the sustained and systematic metaphor, not only (most notably) for the universe and the body, but also for the structure of the mind. In outlining the structure of human reason Descartes transformed the machine-as-idea into the idea-as-machine, representing the process of thought as the same ordered series of relationships between discrete parts, following one another exactly and ordered to

[76]The place of the imagination in Descartes' concept of intellection has been reassessed recently (and its importance much emphasized) in *Descartes's Imagination*.

an end. The excellent operation of reason is said to involve a continuous motion of truth-transfer by means of discrete stages in the "order of reasons."[77] The last stages in any process of reasoning must be completely regulated by all those that came before in order to avoid a breakdown in the "mechanism" of thought. The benchmark of Cartesian philosophy is a method that will guarantee the certainty of human rational processes, and he believed that he had found this method in his universal geometry, the technique of reasoning in deductive chains. He wrote in the *Discourse on Method*: "Those long chains of reasoning, simple and easy as they are, of which geometricians make use in order to arrive at the most difficult demonstrations, had caused me to imagine that all those things which fall under the cognizance of man might very likely be mutually related in the same fashion."[78] The steps of this reasoning, like the geometry in which they are rooted, are grounded in the deep metaphor of the idea of the machine, a mental model that follows mechanical guidelines. This style of thinking goes a considerable way toward explaining both Descartes' conception of his lens grinding machine, as well as his frustration with the authentically "mechanical" difficulties—difficulties with friction, misalignment, and the plasticity of fruitwood and brass under changing conditions of temperature and humidity—that impeded its realization: believing that human thinking processes should follow the organization of a machine, he came to believe that the organization of a real machine should follow his thinking process; having mechanized his geometry by defining curves in mechanical terms, he came to believe that he could construct a machine out of his geometry. Having mechanized reason, he believed that he could reason his way to a physical machine to grind lenses. Tellingly, the man Descartes sought out to build his machine was not an opticus (who might know something about working with glass) but a maker of mathematical instruments.

The Mechanical Philosophy and Its Communities

Descartes' thinking on these matters belongs to the constellation of ideas that has come to be called the mechanical philosophy, and there can be little doubt that Descartes' project to build a new kind of machine—automatic, precise, capable of making an artifact traditionally within the purview of an established artisanal tradition—merits consideration in light of this broader association of mechanistic explanations distinctive of the new sciences.

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[77]See the classic study by Guéroult, *Descartes, selon l'ordre des raisons*.

[78]Adam and Tannery, *Oeuvres de Descartes*, Vol. 6, pp. 19–20; translation from Grosholz, *Cartesian Method*.

Efforts to explain the origin and content of the mechanical philosophy have called into service everything from Democritus to double-entry bookkeeping, and a growing recognition of the instability of the term has led to reevaluations of its coherence as an analytical and historical category.[79] Work done on the subject in the mid-twentieth century focused on the mechanical philosophy as a systematic effort to banish "occult qualities" from nature, a process ostensibly aimed at leaving to investigation nothing more (or less) than matter in motion.[80] Emphasis here fell on the Renaissance rediscovery of Greek and Roman matter theorists preoccupied with atomism. If the place of classical matter theory in any characterization of the mechanical philosophy is assured, more recent studies have called into question both the correctness and the utility of understanding the pursuit of mechanical philosophy as a clean-sweeping of the supernatural weevils lurking in the closets of the early modern imagination.[81]

The important, if not absolutely constitutive, role of the practical mathematical sciences in the formation of the mechanical philosophy has been demonstrated (particularly in the English context) by J. A. Bennett, who has shown that the practitioners of ars mathematica of the practical sort were preoccupied by the application of geometry and calculation to the solution of concrete problems in astronomy, navigation, and instrument making.[82] Although there has been a tendency to place these mathematical practitioners in the "empirical" tradition of the artisan-engineer—as distinct from the "high" mathematical sciences[83]—Bennett's analysis has moved toward undermining this distinction, in part by demonstrating how many of the seventeenth-century figures characterized as mechanical philosophers also engaged in the practical mathematical sciences. At issue is both an intellectual question—To what degree did certain fields of practical inquiry (e.g., navigation, cartography) and their respective instruments (e.g, compasses, barometers) serve as important fields for the thinking (e.g., on geomagnetism, on the weight of the air) that became central to the mechanical philosophy?—and an associated sociological question: In what ways has a traditional historiography of the seventeenth century emphasized the classical philosophical (and by extension distinctively elite) genealogy of the mechanical philosophy at the expense of recognizing its roots in what Bennett calls the "mechanics' philosophy"?

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[79]Gabby, "Mechanical Philosophy and Its Problems."

[80]See, for instance, Boas, "Establishment of the Mechanical Philosophy"; and Dijksterhuis, *Mechanization of the World Picture*, section 4.

[81]One version of this critique can be found in Hutchinson, "Supernaturalism." For another, see Schaffer, "Godly Men." See also Bechler's rejoinder in "Essence and Soul."

[82]Bennett, "Mechanics' Philosophy and Mechanical Philosophy."

[83]See, for example, Kuhn, "Mathematical versus Experimental."

The telescope fits well into this framework: its development was driven by practical demands (including military enthusiasm), even as its workings prompted new investigations of optics, mathematics, and (of course) astronomy; at the same time, as discussed above, at the core of the instrument's power lay a novel collaboration of mathematical philosopher and practical adept. It will be the thesis of chapters 2 and 3 that although the common project of the telescope drew the natural philosopher and the mechanical practitioner closer together, Descartes' preoccupation with the mechanization of the process of lens making (and the commitment to mechanical lens making shared by his contemporaries) betrayed a deep ambivalence on the part of the intellectual elites toward this new dependency. The project to make telescopes may have brought the scholar and the craftsman into a new form of cooperation, but the project to mechanize lens making can be understood as an effort to end this new and interdependent relationship.

What is at issue here is nothing less than the relationship between the mechanical philosophy and actual machines (and their makers), a subject that has given rise to a growing literature.[84] As Brian Baigrie has recently suggested: "Much work remains if we are to reconceptualize Descartes' mechanism as a very particular take on machines and the mechanics of machinery."[85] The hyperbolic quest, as I will try to show in chapter 2, provides a superb window onto this problem. After all, Descartes worked very hard to demonstrate that there was a true and certain connection between his ideas and the world, and yet in the project to build the mechanical lens machine, physical matter could not be made to operate as pure extension, the reification of geometry that was the stuff of his idea of the machine. This implicated the craftsman, who was responsible for translating the idea of the machine into a physical machine, of compelling physical matter to behave exactly like mental matter: any failure of the machine was his failure.[86] In Descartes' view the shortcomings of craftsmen lay in their being insufficiently mechanical: they were not entirely scrutable in mechanical terms, and therefore the path to perfected lens making lay in the mechanization of the craftsman, more automation, and the alienation of the hand of the artisan.

[84]Shea, "Rise of the Mechanical Philosophy." Also see Price, "Origins of Mechanism"; and idem, "Philosophical Mechanism."

[85]Baigrie, "Descartes's Scientific Illustrations," p. 101.

[86]Shapin ("Invisible Technician") suggests that the "invisible technicians" of seventeenth century become "visible" only when experiments or demonstrations fail. See also the expanded version of this article that appears as chap. 8 of idem, *Social History of Truth.*

Interestingly, in classic Marxist thought the relationship between techniques of production and the mechanical philosophy (particularly where Descartes is concerned) has been interpreted in a manner quite the reverse of what I have begun to suggest here.[87] According to this tradition it was the relentless and profit-driven division of labor itself (and the increasing capitalistic analysis of the mensurable dimensions of "work") that gave rise to the abstractionist explanatory approaches of the mechanical philosophy. Although this argument came under severe criticism at the time, perhaps not enough effort has been made to show that the causality could run very much the other way: the mechanical philosophy had direct implications for concepts of craftsmanship and manufacture in the period.[88] It will be my aim in chapter 3 to address this issue in a single important arena: lens making machines and the craftsmen who were called upon to make devices explicitly conceived to replace them.

In considering the relationship among human makers, the mechanical philosophy, and machines themselves, some commentators have been tempted to assert that both the ideas and the devices proceed from some deep human predilection for mechanical explanations; another (and more promising) enterprise has set out to understand the significance of a medieval, and ultimately classical, tradition of mechanical and mathematical analysis of the simple machines.[89] Treatises like the *Mechanica* of Pseudo-Aristotle both offered something akin to a mechanical lexicon—by identifying and describing the five (or sometimes more) simple machines thought to compose more complex mechanical devices[90]—and useful rule-of-thumb analyses for determining mechanical advantages. Interestingly, references to Descartes' work on a treatise of his own in this very tradition, entitled "The Mechanics," date to precisely the same period as his work on the proportional compass as well as his earliest interest in lenses.[91]

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[87]Borkenau, "Mechanistic World-Picture" (a translation of "Zur Soziologie des mechanistischen Weltbildes" of 1932).

[88]See Grossmann, "Social Foundations," (a translation from "Die gesellschaftlichen Grundlagen der mechanistischen Philosophie und die Manufaktur" of 1935). It should be noted that in his effort to place machines at the origin of the mechanical philosophy Grossmann overlooks precision mechanics, focusing instead on power systems and banausic devices.

[89]Despite its originality, Price's "Origins of Mechanism" tends in the first direction. For the second program, see Micheli, *Le origini del concetto*; Gandt, "Les Mechaniques attribuées à Aristote."

[90]These were the screw, the wedge, the lever, the windlass, and the capstan. These last two were distinguished essentially by orientation, the capstan operating on a vertical axis and the windlass on a horizontal one. For a discussion of the tradition of the "mechanical alphabet" see Ferguson, *Engineering*, p. 139; and also his interesting modern reinterpretation of the tradition in Ramelli, *Various Ingenious Machines*, pp. 560–82. The most elaborate of these compilations of mechanical components would likely be that found in the ten-volume *Theatrum Machinarum* of Leopold.

[91]Gaukroger, *Intellectual Biography*, p. 92.

To understand the significance of this tradition, one need only turn to a text like that of de Caus, who, as his title suggests (*Les* Raisons des Forces Mouvantes avec Diverses Machines tant Utilles que Plaisantes), intended to give his readers much more than a mere grab bag of mechanized novelties and table fountains. His was a compendium of pleasing machines that was explicitly grounded in a precedent account of *les raisons des forces mouvantes*, with emphasis on *les raisons*. He began with a definition of a machine (borrowed from Vitruvius) not unlike what I have called the "idea of a machine" that served so important a role in Descartes: a machine, according to de Caus, "is an assemblage and firm conjunction, of joinery or other material, having force and movement." After laying out this and a set of related definitions, de Caus proceeded in the manner of a geometry text: going from "definitions" (four) grounded in scholastic matter theory; to "theorems" (eighteen) in which he laid out the operation of the mechanical "units" out of which his more intricate devices would be composed; and concluding with a host of "problems" phrased as "constructions" in the geometric sense ("To create a fountain in a grotto where a figure of Echo . . . ") which he "solved" by means of his designs. The significance of the structure of a text like this lies in the evidence it provides of an established project to "geometrize" mechanical systems, and the origin of this work in the attempt to "build up" mechanical devices out of a set of simple (Euclidian) definitions.

If the mechanical philosophy implied thinking about the world in terms of machines, books like that of de Caus strongly suggest a tradition of "philosophizing about machines" that used geometry as its model and sought to use geometrical "constructions" to emulate the natural world by constructing elaborate automata.[92] That Descartes was familiar with such works casts considerable light on his own contemporary efforts to use a mechanistic framework, rooted in geometry, to explain nature. In a broader sense, the whole late Renaissance corpus of mechanical theaters can be seen to have contributed important elements to the mechanical philosophy in general and to the thinking about machines that gave rise to Descartes' mechanical lens making device in particular. First, the "speculative" (or "fanciful") quality of the machines they so often depicted was exactly a product of a sophisticated mechanical analytic: if there were five (or six, or fifteen) fundamental mechanical units, then "machines" could be designed by means of the composition of these elements;

[92]Bedini, "Role of Automata."

the task of the engineer-author was to use this mechanical lexicon to compose elegant mechanical prose, orotund and lengthy phrases of mechanics in which no mechanico-syntactic rule was broken.[93] In other words, such devices embodied the very principle of the "idea of the machine" (an ordered series of relationships between discrete parts, following one another exactly and ordered to an end) so important to Descartes. Second, the form taken by many of these devices was that of the automaton, a device that became the central metaphorical conceit of the advocates of the mechanical philosophy.[94]

It was Hooke, later in the century, who would refer to his lens grinding machine explicitly as an "Automaton," but Descartes clearly conceived of the composite mechanization of the work of the lens craftsman in parallel terms.[95] His interest in automata achieved mythic status in the (doubtless apocryphal and more or less prurient) tale of his fabrication of a female companion named Francine and her demise at the hands of an agitated sea captain who stumbled upon her in Descartes' effects.[96] Of his interest in the mechanized fountains of Saint Germain-en-Laye, depicted in de Caus, more tangible evidence exists.[97] Close attention to de Caus' treatment of the fountains reveals a striking coincidence: a number of his proposed fountains worked on the principle of the expansion of air in sealed leaden reservoirs, which powered pneumatic or hydraulic automatons that whistled or moved; several of these devices depended on the gradual heat of a rising sun to initiate their subtle movements; in the most sophisticated designs, however, de Caus turned to the augmentation of the power of these devices by the addition of batteries of convex glass lenses, either affixed to the tanks or arranged in batteries to focus on them (Figure 12). Could there have been lenses in the fountains of Saint Germain, given that the Florentine brothers Francini (Tomasso and Alessandro), who designed them for the queen, were kinsmen of a certain glassworker of Florence in the service of the Medicis, Ippolito Francini, who came to be such an aid to Galileo's lens grinding projects? Until further evidence comes to light, that is speculation. What is clear, however, is that in turning the pages of de Caus, Descartes saw automated systems whose regular motions were produced by

[93]For the origins of the favorable valuation of intricacy itself, one need look no further than the aesthetics of Mannerism. See Jardine, "Astronomy in Early-Modern Culture."

[94]For an exhaustive catalogue of the power and durability of this metaphor, see Mayr, *Authority, Liberty and Automatic Machinery*. Also useful is Bredekamp's *Lure of Antiquity*.

[95]Hooke quoted in Iliffe, "Material Doubts."

[96]Gaukroger, *Intellectual Biography*, p. 1.

[97]See n. 58, supra.

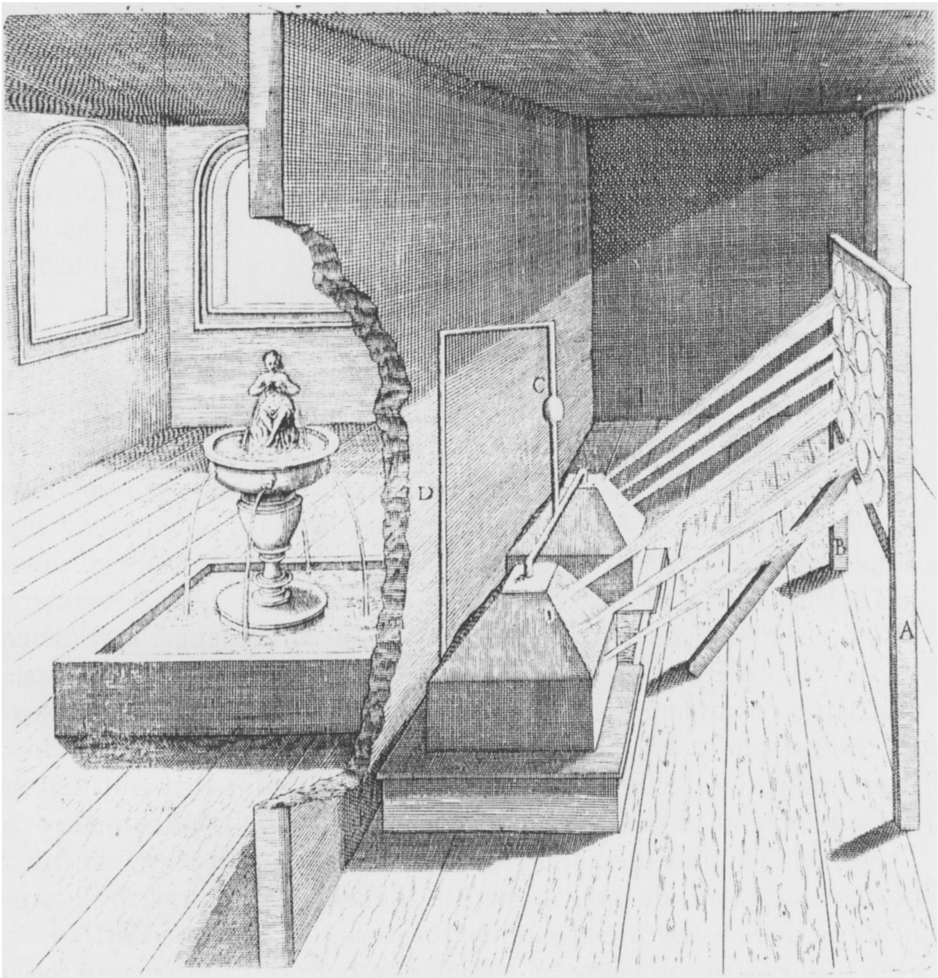

Figure 12 De Caus' fountain (Caus, *Les Raisons des Forces Mouvantes,* p. 22)

lenses; shortly thereafter he conceived of an automatic system whose regular motions produced lenses.

It is to his project to realize that precision instrument—a lathe that mechanized geometry—that I now turn.

2

In Pursuit of the Curve

DESCARTES AND FERRIER: MINCING WORDS AND MIXING WORLDS

There is good evidence that work on making hyperbolic lenses by hand preceded Descartes' proof of the solution to the anaclastic. Isaac Beeckman was already a celebrated mathematician when Descartes made his acquaintance in Holland in 1618 at the age of twenty-two. The older savant and the young soldier met over a geometry problem posted at the town of Breda, where Descartes was garrisoned. His quick and elegant solution drew the attention of Beeckman, and the two men, despite several celebrated fallings-out, remained in contact until Beeckman's death in 1636.[1] Beeckman did not survive to see the publication of *La Dioptrique* in 1637 and thus did not witness the sudden popularity of the hyperbolic lens, a project he pioneered as early as 1622.

Whether Descartes played a role in Beeckman's early effort to produce an "astigmatique" lens can not be clearly determined. The entries in Beeckman's journal seem to refer only to the work of Kepler, whose earlier formulation of the anaclastic was mentioned above, but it is evident that Beeckman thought he would resolve the problem of color fringes with a new hyperbolic lens shape.[2] By 1629 Beeckman was fully aware of the work being done by Ferrier under Descartes' direction, yet the work Beeckman did himself with a young artisan in the early 1620s may well have been independent of Descartes. The dispute, however, that temporarily broke the relationship between the two men, concerned, apparently, Beeckman's attempt to pass off

[1]Haldane, *His Life and Times*, pp. 43, 163.
[2]De Waard, *Journal tenu*, Vol. 2, p. 210 and Vol. 3, p. 234.

Descartes' work as his own as early as 1618; therefore whether the hyperbolic work that led Beeckman to employ a "lunetier" was inspired by interaction with the young Descartes at Breda seems impossible to resolve.

What is certain is that Beeckman's "garçon," who was in his early teens, succeeded in making at least one approximately hyperbolic lens before 1624 by hand grinding the borders on a spherical lens in order to make it more hyperbolic in profile.[3] Similar approximations were used later in the century.[4] The fairly small number of references to the undertaking in Beeckman's exhaustive four-volume folio journal indicates that, though he may have had high hopes for the project, the results were less promising. Beeckman put the project aside in the late 1620s, probably after learning in 1627 about the progress of Descartes and Ferrier working in Paris.[5]

René Descartes returned to Paris in 1623 after a nine-year absence from France, during which he had served in the army under Prince Maurice of Nassau in Holland; Maxmillian, Duke of Bavaria; and Count Boucquoi of Hungary. He had participated in the sieges of Breda and Pressburg and watched the imperial Bavarian army decimated by Hungarian mounted swordsmen at the Battle of Neuhausel. During his travels with these armies he had won the respect and admiration of a variety of military engineers and savants, some of whom would become part of his circle on his return to Paris. In Paris, Descartes also found himself in the company of Claude Mydorge and the Père Mersenne, both of whom he seems to have known from his days as a student before 1615.[6] It was during this period, before the self-imposed exile in Holland, that Descartes applied himself to the proof of the anaclastic, and during this time that he met aspiring young mathematical and mechanical practitioners like Ferrier, De Beaune, and Morin, the men who would try for the next twenty-five years to realize the hyperbolic lens making machine.

Available sources offer little on the man Ferrier: all that can be stated with certainty is that he was a promising young artisan and mechanical practitioner from Auvergne who had begun to build a reputation for himself as a craftsman and builder of mathematical instruments. Most important, he had managed to attract the attention of Descartes and had been thus introduced into his circle of savants

[3]Ibid., Vol. 2, pp. 210, 295.
[4]See chap. 3, below.
[5]For Beeckman's knowledge of Ferrier's work see ibid., Vol. 3, p. 97.
[6]Haldane, *His Life and Times*, pp. 37, 38.

and mathematicians in Paris. Descartes clearly thought highly of Ferrier, writing in a letter to an acquaintance that he was a man skilled in the "science of miracles" capable of realizing things thought to be the domain of "magicians aided by their demons."[7]

Evidence for how close Descartes and Ferrier had become by the end of the 1620s is provided by the first letters that Descartes wrote back to Paris after his departure for Holland in 1629. One of the earliest was a cordial letter inviting Ferrier to join him in the low country where they could "live as brothers," and apply themselves to a continuation of the work they had begun on lens making. Descartes promised to pay all his expenses, including the cost of return passage to Paris should the young craftsman prove unhappy.[8] In 1629 Descartes thus had high hopes for the lens making project on which he had embarked with Ferrier while in Paris.

What work had they done together? Although there is no correspondence or journal that records their progress while in Paris, there is evidence that under Descartes' direction Ferrier had succeeded in fashioning some small hyperbolic lenses, though the possibility of mechanizing the system for lens making had not yet been explored. This evidence for the limited success of Descartes' and Ferrier's work together in Paris before 1629 lies in the introduction to Jean-François Nicéron's 1638 work on drawing, catoptrics, and trompe l'oeil, entitled *La Perspective Curieuse*. Publishing the year after *La Dioptrique*, when the enthusiasm for the promise of the new hyperbolic lenses must have been at an all-time high among the savants of Europe, Nicéron took advantage of his acquaintance with Ferrier to demonstrate that he was up to date with the cutting edge of the new sciences, writing:

> And the invention of the telescope has since its discovery been, thanks to God, very well developed, by means of many good souls and learned men who have made many excellent speculations and diverse experiments on this subject in order to perfect it. Among these we include Galileo, Daca [de Valdes], de Dominis, Kepler, Sirturius[9] who all wrote on this business, as well as, most recently, Monsieur des Cartes, who in his Dioptrique, out of a theory which he explains scientifically, informs us of extraordinary and useful practices out of which we hope to see wonderful effects, through the work of Monsieur Ferrier who has undertaken the work. And truly if anyone is capable of succeeding

[7]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 21.

[8]Ibid., p. 14.

[9]Sirtori's book served as Beeckman's early instruction on lens making for telescopes, see De Waard, *Journal tenu*, Vol. 1, p. 208.

> at this new invention, it must be avowed that it would be he, because, besides the excellence of his hand and his extensive experience in these matters, he has special knowledge of the author's secrets. This can be demonstrated by the sample which he has shown to his friends, which is a viewing tube with a small hyperbolic lens which separates and magnifies all types of tiniest objects whose size hides them from the view of even the most perceptive. It does this so well that we must say that not only will we receive a great benefit in these types of devices but also great advantages. . . . [10]

The only problem with Nicéron's complimentary account of his friend's progress is that it belies the truth about Ferrier's continued participation in the project. By 1638 Ferrier appears to have been out of touch with Descartes for at least five years. Despite the promise of his early work, Ferrier's unwillingness to follow Descartes to Holland in 1629 and some miscommunications had resulted in a rupture with his friend and sponsor. Descartes, aided by Constantijn Huygens, had secured a new "tourneur" by 1635, and even if Ferrier had held onto the precious letters of 1629 outlining the "secrets of the author," by March of 1638 Descartes saw fit to write to Père Mersenne concerning Ferrier's continued efforts: "Let him work, it is a great show that will achieve nothing, and I believe that the least little 'tourneur' or locksmith would be more capable than he of illustrating the effects of these lenses."[11] Either Ferrier was misrepresenting the state of his relationship with Descartes to Nicéron, or Nicéron was being generous for the sake of his friend's reputation. More important, given Descartes' attitude in 1638 toward Ferrier's progress, it seems unlikely that he had recently achieved any hyperbolic lenses worthy of passing around in the learned circles of Paris. If he had, he surely would have let Descartes know in the hopes of winning back his favor—as, indeed, he later attempted to do. In short, it is probable that the sample Ferrier was brandishing in the wake of the publication of *La Dioptrique* was actually the result of work done under Descartes' direction in Paris before 1629.[12]

Clear evidence that the striking step toward the mechanization of the lens grinding process had not occurred during Descartes' time in Paris is provided by Descartes' early correspondence with Ferrier from Holland. It is in these letters that we read the full mechanical description of the lens grinding machine, presented to Ferrier as a

[10]Nicéron, *Perspective Curieuse*, pp. 101–2.
[11]Adam and Tannery, *Oeuvres de Descartes*, Vol. 2, p. 85.
[12]The same conclusion is reached by Descartes' editors. See Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 444.

detailed treatment of the "machine that I described to you before I departed." Thus it seems certain that whatever work Ferrier did on hyperbolic lenses under Descartes' direction in Paris before 1629, it did not include work on a hyperbolic lens grinding machine, although Descartes' mechanical inspiration can apparently be dated to early in that year.

Although the device passed through several different designs, the basic principle of the machine remained unchanged from Descartes' original formulation of early 1629, which can be reconstructed from his letter to Ferrier from Holland on October 8 of that year (Figure 13): An acute angle (BCD), formed out of wood, was to be fixed in such a way as to rotate, one of its sides (ACB) serving as a horizontal axis. Thus turned, the free limb of the angle (CD) evolved a cone in space. A table (shown here in cross section and with a double top, HG and IK) defined a plane cutting that cone parallel to its axis, and therefore in that plane the path of the limb CD traced a hyperbola. If the limb CD were a file, then a flat metal plate (shown in the upper diagram in cross section as the line NM; and in the lower diagram in a top-down view as the polygon PNOM), pushed on the table against the swinging file, would gradually be ground on the edge PNO to a hyperbola. This metal plate could then be used to cut the edge of a grinding wheel to a hyperbolic form, and the application of the glass blank to the periphery of the wheel (both spinning, on perpendicular axes) would result in a hyperbolic lens.

Relatively early, Descartes advocated dropping the simple idea of having the limb CD be a file, and pressed for a version of the design that would later be published in *La Dioptrique* (see Figure 2, to which the reader has been introduced in chapter 1), whereby a roller (shown in detail here, Figure 14) slid on the limb in such a way as to remain

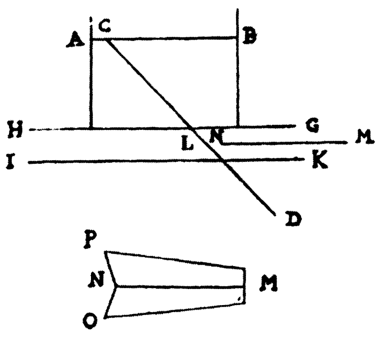

Figure 13 Sketch of Descartes' machine (Adam and Tannery, *Oeuvres de Descartes*, Vol. I, p. 34)

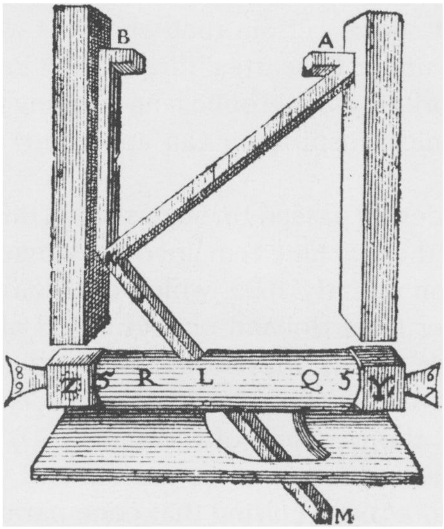

Figure 14 Roller in Descartes' machine (Adam and Tannery, *Oeuvres de Descartes,* Vol. VI, p. 219)

in constant contact with the table; the ends of this roller—which served as a kind of stylus—could be armed with a variety of cutting tools. Much of the actual experimentation with the initial versions of the hyperbolic machine, however, focused on the simpler scheme of having a file attached directly to the rotating limb, without the additional complexity of the sliding roller. For instance, the design on which Ferrier worked for some time (Figure 15) had no complicated roller-joint, but it did feature an adjustable limb that could be set at different angles to evolve different cones, and hence to produce different hyperbolic forms. Adam and Tannery claim that Descartes was probably withholding this latter design, with its added flexibility, by not publishing it in his *La Dioptrique*—the suggestion being that he wished to keep the best plans for the hyperbolic machine to himself and his immediate circle.[13] But this seems unlikely.[14] It is much more likely that this "simpler" design was rejected because it did not allow the hyperbolic tracer to cut directly the periphery of the grinding wheel, a step Descartes forcefully advocated as part of his general

[13]Ibid., p. 228.

[14]The strongest evidence that Adam and Tannery are wrong in this assertion is found in a series of letters written by Descartes in 1639 to Florimond De Beaune, the young savant of great promise who worked on the project until injured by a piece of broken glass in 1640. The machine discussed in this correspondence is the same machine outlined in *La Dioptrique*. The two men even refer to its parts by the letters used on the plates of the book. Descartes would hardly have kept a secret plan from the most promising artisan he knew. (See ibid., Vol. 1, p. 630 and Roth, *Correspondence of Descartes*, p. 131.)

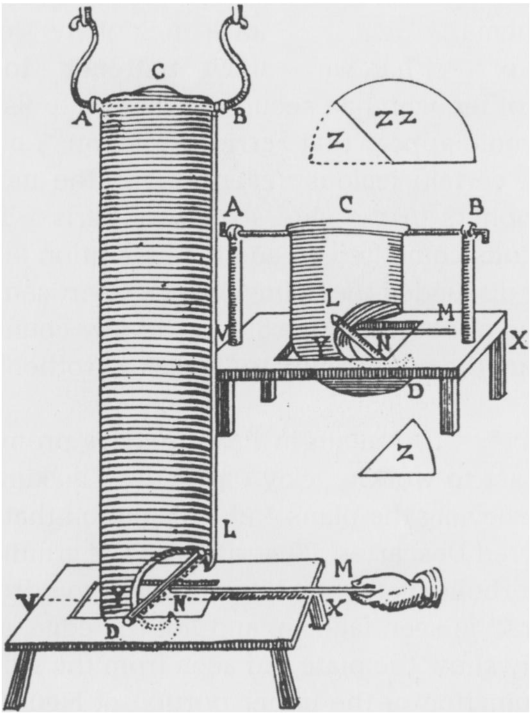

Figure 15 Another design for Descartes' machine (Adam and Tannery, *Oeuvres de Descartes,* Vol. I, p. 56)

commitment to mechanization, a commitment he consistently manifested by compounding mechanical processes in his efforts to exclude manual manipulation within the system wherever possible (and, indeed, often when not possible, too—as his artisan-collaborators would try to explain). Descartes sought to make his machine automatic.

Having received both an invitation to Holland and a description of the lens grinding machine in Descartes' letter at the end of 1629, Ferrier decided that he would stay in Paris and work on the machine there, under long-distance supervision. It is possible to reconstruct the young craftsman's preference for remaining in Paris from other portions of the correspondence. Through a circle of savants and prelates, Ferrier hoped to win for himself accommodations in the newly built addition to the Louvre, which had apartments for royal instrument makers.[15] There is evidence that Ferrier had benefited from the

[15]Another "Ferrier" (Antoine) had been in possession of such chambers in 1608 (see n. 1 of the introduction, supra).

confidence of Descartes, in that he is known to have received a commission for a mathematical device from Jean-Baptiste Morin, Descartes' friend, and the project had won sufficient attention to attract the aid of the king's brother, who had secured precision tools from Germany for Ferrier. It would appear that Ferrier's relationship with Descartes had inspired a certain jealousy even among the more established natural philosophers in the elite society of Paris.[16] The promise of further prestigious commissions and the aspiration for a place in the court probably dissuaded the young provincial artisan from abandoning the glamour of city life for exile in the low countries, even if it meant passing up the opportunity to "live as a brother" with a prodigy like Descartes.

Having decided to remain in Paris, Ferrier promised Descartes that he would set to work quickly on the lens making machine, and he began by reviewing the plans and explanation that Descartes had sent. He corrected Descartes' illustration of the grinding wheel being cut by the hyperbolic plate, pointing out that "you drew the wheel in this first illustration seen face-on, and not the edge, and that is why you should only show the plate NM seen from the side and not lying flat."[17] An examination of the upper portion of Figure 16 shows this criticism to be valid. Ferrier proceeded to pass along a handful of very practical problems he saw in the design laid out by Descartes. Among these, he thought that the idea of having interchangeable cutting shafts (see CD in Figure 13) would not work, even though it would be nice in theory (allowing a "rough" file and progressively

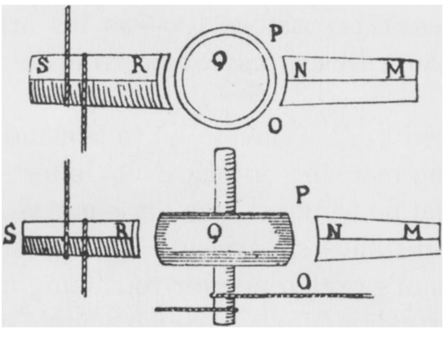

Figure 16 Proposed grinding wheel (Adam and Tannery, *Oeuvres de Descartes,* Vol. I, p. 35)

[16]Mydorge was particularly irritated by Descartes' relationship with Ferrier, as will be seen later in this chapter.

[17]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 42.

finer blades). The problem would arise, he asserted, in getting those different shafts to fit into the same hole in the axis AB firmly enough that there could be no variation in the angle BCD. Any joint that allowed fitting and refitting would come loose under the forces and friction of the work. Pointing out another difficulty with the design he wrote, "As for the material for the wheel Q, there does not exist any kind of stone, not even diamond, that can grind down glass without putting some abrasive between the surfaces." Descartes' idea of a slate whetstone would never work. Ferrier pointed out that the glass would be harder than everything else, harder than the hyperbolic plate, the wheel—everything—and as a result, everything would tend to be deformed by the spinning glass blank.[18] Such wisdom would have been apparent to anyone who had ever ground a lens in the traditional metal pan or form, and the comments characterize the gap between the speculative mechanics of the natural philosophers and the craft experience of the mechanical practitioner. Pans had to be carefully re-turned, and the same pan would produce a sequence of lenses of gradually increasing focal lengths as it was deformed through use.[19] Ferrier ultimately suggested a vertical lathe (Figure 17) and a metal grinding wheel that was to be dusted with abrasives.

Ferrier closed the letter by complaining of how he had been treated by some of Descartes' friends since his departure. For instance Mydorge had been particularly unhelpful, probably because he had already set about finding his own assistant, and was embarking on a rival project to make hyperbolic lenses. Perhaps to introduce tension

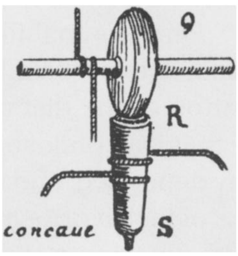

Figure 17 Vertical grinding wheel (Adam and Tannery, *Oeuvres de Descartes*, Vol. I, p. 47)

[18]It is interesting to note that in the design for the machine presented in *La Dioptrique* in 1637 (see Figure 2), a bin containing the abrasive and perhaps some water is situated under the grinding wheel so that the supply of abrasive may be constantly replenished by the rotation of the wheel (Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 223). It was Ferrier who taught Descartes that tripoli powder (or some other abrasive) would be necessary, because in 1629, Descartes had imagined making the wheel out of an abrasive stone.

[19]McKeon, "Adrian Auzout," pp. 118–19. (This is a doctoral dissertation presented at the Sorbonne in 1965; I have consulted the copy deposited at the library of the Observatoire de Paris.)

between the two friends, Ferrier suggested that Mydorge had been passing off Descartes' anaclastic proof as his own. Using this indictment of Mydorge as a lead into the issue of the anaclastic, Ferrier asked Descartes to explain to him again the compass construction of the anaclastic curve for a piece of glass with a particular index of refraction, which Descartes had explained before he left, but which Ferrier had lost.

Descartes replied promptly, beginning "you gave me great pleasure in conducting me along through the difficulties you had with what I sent you." In this letter Descartes' drawing of the machine is an actual illustration (see Figure 15) and no longer a schematic diagram. In looking at this drawing of the machine it is evident that at an early stage Descartes still conceived of the hyperbolic lens grinding machine more as a tool to aid and direct the craftsman than as an automated system for mechanical making: a hand works upon the device in the illustration. At this time relations with Ferrier the artisan were good, and Descartes retained considerable hope for the collaboration. Descartes addressed the points raised by Ferrier as best he could, suggesting a way that the cutting bars (see DL in Figure 15) might be made interchangeable by having them fit into a sickle-shaped mouth at the desired angle. But, because he did not suggest how the cutting bars were to be held in place, Descartes did not really address Ferrier's primary concern—that these "joints" would not be solid.

Before undertaking another explanation of the compass construction of the anaclastic, Descartes vented some frustration: "But I clearly see that you have forgotten a little of what I told you concerning this in Paris, so I must rub my brow a bit and make myself write it all down for you once and for all."[20] Ferrier's inability to recall this relatively straightforward construction, and his maladroit posing of the question itself, gives another indication of the distance separating the mathematical spirits of the mechanical philosophy from the mechanical practitioners on whom they depended, and Descartes' frustration with the mathematical weakness of his favorite instrument maker intimates the broader frustration with craftsmen that would coincide with his increasing efforts to mechanize the process of precision making.

At this time Ferrier was serving as a general liaison for Descartes in Paris, keeping him informed of what went on and doing errands that would have been inappropriate for Descartes to request from his older and more venerable friend, Mersenne; such services were part of the relationship between craftsman and patron. Though much of

[20]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 62.

this mundane side of the correspondence was omitted by Clerselier, who edited and collected Descartes' letters after his death, some of it can be reconstructed from other sources. For instance, this letter, like many others, included a list of "commissions à Paris" for Ferrier, including a request that he discover whether Balzac, Descartes' friend since 1626, would be in Paris for the winter. This particular errand survives, because Descartes had to ask it of Mersenne five months later, writing that Ferrier

> has been so long in writing me, even after he received letters from me to which anyone else would have thought it impolite not to respond: because besides my having explained to him a lot of things which he wanted to know, I had asked him to write me concerning a whole bunch of little things, to which, it seems to me, he might have at least responded.[21]

By March of 1630 Ferrier had managed to alienate Descartes by never responding to his detailed instructional letter of October. Fraternal feelings had evaporated by the time that word reached Descartes, through Mersenne, that Ferrier seemed to have changed his mind about coming to Holland. The prospects for the Louvre were probably seeming dimmer and dimmer to him, particularly after Père Condren, Ferrier's closest link to the court, was promoted to a distant bishopric and left Paris. At the same time the pressure was building to complete the instrument Morin had commissioned, now long overdue. With Mydorge as a rival and no patron arriving to replace Descartes, an all-expense-paid trip to the Netherlands may well have grown increasingly attractive. Descartes was not amused:

> You could not have surprised me more than by writing that Ferrier now talks of coming here, having quit work on Morin's instrument without having accomplished it, because it has been five or six months that I have heard nothing from him. And this, after I sent him two long letters which were more like books . . . . I had decided that he must be engaged in something else and not that he was thinking of coming here, particularly in light of the fact that last year when I invited him he had left me almost no hope. And at that time I was staying in Franeker in a little Château separated from town by a valley and we could have the mass in safety. If he had come, I was ready to buy furniture and take a part of the house so that we could set up separate quarters. I had even secured a boy who knew how to cook French food and resolved to stay put for three years, during which time he would have had everything arranged to complete the designs

[21]Ibid., p. 132.

> for the lenses, and train himself in order that he might afterwards attain honor and profit through his knowledge.[22]

As soon as he had learned that Ferrier preferred to stay in Paris, Descartes threw over all those plans and began to arrange to go to England. Now, he informed Mersenne, it would be very inconvenient for Ferrier to arrive, and Mersenne would do best to inform him

> that I have gone out of the country and he will no longer find me here. And if he should decide to come anyway, thinking himself better off here than in Paris (people who have not traveled have wild imaginations) tell him that life here costs still more than Paris and that he will find fewer interesting people and less work than in the smallest town in all of France.[23]

After all, with all of the special materials and support provided by Morin and his friends, if he could not accomplish anything on the mathematical instrument in three years, what good would he be on lenses?

> I cannot hope that he will succeed on the lenses, for which he will have to make machines that I know are more difficult than [Morin's] instrument. And I would feel foolish if after employing him for two or three years he was unable to realize anything worthy of attention. People might think it my fault.

Descartes was clearly preoccupied by the unseemliness of having his scientific reputation bound to the manual skill of a hired craftsman.

It is difficult to understand why Ferrier neglected to write Descartes for nearly a full year after their initial and extensive correspondence of the autumn of 1629. Given the detailed and critical response Ferrier offered to Descartes' October 8 description of the machine, the argument that Ferrier suddenly felt himself out of his depth seems difficult to support. One possibility is that Ferrier, though he felt comfortable with practical and mechanical concerns like those at issue in the first letter, proved less comfortable handling the more sophisticated geometry outlined in the second. Evidence for this is provided by Ferrier's having complained of losing the piece of paper on which Descartes, before leaving for Holland, had demonstrated the compass construction of the anaclastic. But the construction is not

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22. Ibid., p. 129.
23. Ibid., p. 131.

so complex that it could easily be entirely forgotten. Ferrier may well have lost the paper, but if he had been geometrically adept he should have been able to reconstruct at least some portion of the construction. Descartes himself was not shy about Ferrier's mathematical weakness.[24]

It seems safe to assume that Ferrier wanted to thread his way through the community of Parisian savants as adroitly as possible, and in at least one case, that of Morin's instrument, his zeal to find favor (and commissions) in this circle caused him to overstep his capabilities. We can imagine that after several years of reporting steady progress on the project, so as to encourage his patrons, Ferrier would have found the situation increasingly difficult as he was unable to produce a finished product. The distance between the truth and optimistic progress reports may well have increased over time, a bind not unfamiliar to Ferrier, of whom Descartes once wrote that he did not "lay his account of things as they are but as he would have them."[25] The crisis with Morin's commission was coming to a head at exactly this moment, and between Ferrier's need to extricate himself from that situation and the difficulty he would have experienced facing Descartes' geometry, Ferrier committed a significant political error by not writing promptly to Descartes.

During the time he did not write, Ferrier still seemed to be talking about the lens project in Paris. Descartes wrote Mersenne in April of 1630:

> I am astonished by what you wrote me concerning Ferrier, namely, that he is building his hopes on the invention of the lenses, in so far as he completely neglects to write me. I do not think that I wrote him in enough detail about the machines. . . . But there are people who think that they know everything about something the moment they have seen a hint of light.[26]

While affecting a certain smug distance, and claiming to possess mechanical secrets unknown to a mechanical practitioner, Descartes was manifestly troubled by Ferrier's reticence, and in the same letter to Mersenne he betrayed a concern for the material that Ferrier possessed. "I ask you," he wrote Mersenne, "as a special favor, to write me if he has told you anything of what was contained in the last letters

[24]For a mention of Ferrier's mathematical weakness, see ibid., p. 262.
[25]Ibid., p. 131.
[26]Ibid., p. 138.

that I wrote him; and if he has not said anything about it, I beg you to ask him directly."[27] Evidently Descartes wanted to know whether Ferrier was perhaps absconding with the potentially valuable information in the letters. Would he be willing to talk about their contents? Or would he possibly deny having received them? Did he intend to develop the machines with someone else, in the hopes of greater riches? Had he perhaps already sold their contents to an artisan in Germany or Naples? Such thoughts must have entered Descartes' mind, when after sending the most revelatory information concerning the machine, he failed to get any response.

Sometime between April and November, in a letter now lost, Ferrier put Descartes' mind at ease and managed to make some excuse (which we are left to imagine) for the tardiness of his response. Whatever it was, Ferrier's pen satisfied Descartes enough to reopen communication on the machine. In what must have been the first transaction after their hiatus, Descartes sent Ferrier a set of "cartes," or hyperbolic tracings, which he had had made in Holland. But these tracings became yet another bone of contention. Though we have no record of Ferrier's side of the story, it is fair to say that somehow the cards disappeared. Either they were lost in the mail, as Ferrier claimed, or he received them and chose to deny ever having seen them. Descartes, in his frustration, adhered to this latter scenario: "As for Ferrier, he is misguided to be complaining about the cards I sent him; I am the one who should complain. I paid for them, not he, and maybe he feigns not having received them out of fear of being obliged to me, because I am assured that they were addressed correctly."[28] The disappearance of the tracings could only have increased Descartes' suspicion that Ferrier might have some secret agenda concerning the lenses.

By this time Descartes was clearly fed up with his artisan. He confided to Mersenne: "He's a man of whom I do not think highly, since I have discovered that he never finishes anything he undertakes, and besides that he is very mean-spirited."[29] Descartes did well, however, to request that Mersenne be discreet on the issue, because Descartes' relationship with Ferrier had the potential to cause various headaches. For all Ferrier's difficulties in arranging things for himself in the court, and despite his having alienated Mydorge and Morin,

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[27]Ibid., p. 132. Shea points out (*Magic of Numbers*, p. 199, n. 21) that this was at least in part out of anxiety about preemption on the law of refraction.

[28]Ibid., p. 172.

[29]Ibid., p. 173.

Ferrier still had enough friends in the clergy to raise a public case against Descartes. Although his position may be difficult to imagine, the case does reveal something of the relationships of power and class between aristocratic natural philosophers and the artisans who worked for them. Well looked after while Descartes was in Paris and (we assume) reasonably well provided for, Ferrier benefited from the constant direction, supervision, and encouragement of his patron. He might now claim he had been deserted by his master in the middle of a project he was unable to complete alone. He could argue that Descartes had tricked him into wasting at least three years on a fruitless project and then had left him in the lurch. What would stop him from ascribing his failure on Morin's device and his other commissions to the zealous attention he had given to Descartes' lenses?

Descartes was well aware of these possibilities and how unseemly they might appear. He wrote Mersenne: "If someone thinks that I have done wrong, having shown him affection only to completely abandon him, I wrote you that letter . . . by which you can justify me," there referring to one of the letters, quoted above at length, in which Descartes had explained to Mersenne his willingness to support Ferrier in Holland.

Ferrier was not the only political problem Descartes was facing in November of 1630. Beeckman and Descartes had recently had a falling out, and Mydorge appears at this time to have taken offense at not having heard from his old friend for quite some time.[30] Again Ferrier's name came up, this time offering a clue to the nature of Mydorge's resentment: Mydorge expressed frustration that Descartes wrote more often to Ferrier than to him; given that Mydorge is reported to have spent the fabulous sum of 100,000 écus on making hyperbolic lenses according to Descartes' method, this frustration is more than merely peevish.[31] Descartes was forced to write, again to Mersenne, that "Mydorge is wrong if he takes offense that I write more often to Ferrier than to him; because I want him to know that it is not always to those I esteem and honor the most that I write most often."[32]

Mersenne may have meant well when he put that letter into the hands of Mydorge himself, to put Mydorge's concerns to rest. If so, Mersenne must have neglected to consider what would become of

[30]Haldane, *His Life and Times*, p. 129.
[31]This number appears in Baillet, *Monsieur Des-Cartes*, Vol. 2, p. 326.
[32]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 175.

the long passages directed against Ferrier that were included in the letter, the very same passages Descartes had requested Mersenne to treat as confidential.[33] Mydorge wasted no time in letting Ferrier know of the disdain of his master, and the impropriety Descartes had sought to avoid quickly escalated into an open confrontation.

Ferrier took his complaints of character defamation and abandonment to the circles into which he had been introduced, at least in part, by Descartes himself. By the end of November, Ferrier had secured letters of reproach and testimonials of character from Pierre Gassendi, an esteemed savant; Henricus Reneri, a philosopher and Descartes' personal friend; and Père Condren, now a ranking cleric in the Oratory and confessor to Gaston D'Orleans; in addition to two other members of the court clergy. These letters were bundled into a weighty packet that arrived in Amsterdam on Saturday, the 30th of November, 1630. Descartes wasted no time with his response, putting three letters—one to Condren, one to Ferrier himself, and a last to Mersenne—in the post on Monday.

The letter to Ferrier recounted from Descartes' point of view what had happened over the last two years: "I have taken up my pen so that once and for all I can clear away all of your complaints, and explain to you my actions," he wrote. "If I had known your personality and your affairs from the beginning, I never would have counseled you to work on what I thought concerning refraction." Descartes claimed to have shouldered even the mechanical minutiae that rightfully were the responsibility of an able mechanical practitioner, not of a philosopher, writing: "having come to know of the difficulties that had stopped your progress, I had pity for the time you were wasting on the project, and out of my love for you *I descended to consider the very least mechanical details*." Descartes pointed out that Ferrier had suddenly stopped writing despite all this attention, despite Descartes' having volunteered to pay all the investment and give up all the profit. Descartes' defense was methodical, though still eloquent: Ferrier had been warned of the difficulty of the task, had accepted it, and had always been treated with great respect. Concerning the insults recorded in the letter to Mersenne and now well known in their circles, Descartes wrote: "You know well that if I had really wanted to ruin you I would have done so more than six months ago, and if a few words of mine that have come to light have given you great displeasure, my prayers, and my thoughts and the assistance of my friends have not then been

[33]Shea treats Mersenne's indiscretions (*Magic of Numbers*, p. 199, n. 21).

any less important."[34] He closed the letter with a touch of disdainful bravado, by offering to open the case before those who knew what had transpired. If this informal tribunal should find any fault with Descartes' comportment, he would be content to make whatever reparations were deemed suitable.

The letter Descartes penned to the reverend Condren made much the same offer, in a more humble tone: "I hope that if you find that I have failed, you will oblige me by not flattering me at all, for I will not fail to obey exactly all that you command."[35] Of course, Descartes played his trump card in the network of connections when he informed Condren that "I have begged the Reverend Father Mersenne, who knows perfectly the whole affair, to please inform you about what has happened." This said, Descartes took out a third sheet of paper and wrote a letter to Mersenne explaining how to present his defense to Condren. Descartes asked Mersenne to pick out the letters in which he (Descartes) had recounted the preparations made in Holland for Ferrier's arrival and the eventual refusal of this invitation. Mersenne was asked to go and see not only Condren, but also Reneri, Gassendi, and Gibieuf to present Descartes' account of his own "prudence and moderation" in the face of the "petty scheming" of his workman.[36]

In this way Descartes was able to extricate himself from the suit of Ferrier, an incident one of his biographers calls a "situation of considerable difficulty."[37] Ferrier's complaints were deflected, and Descartes' former friend became more or less part of the Parisian landscape. About one year after the imbroglio, Descartes queried Mersenne: "I would like very much to know if Ferrier is still in Paris and if he still talks about lenses."[38] Mersenne's response is not known.

For all the unpleasantness that Ferrier occasioned in 1630, Descartes' commitment to the project of grinding hyperbolic lenses kept him curious about the whereabouts and progress of his former assistant. In 1632 Descartes wrote:

> I have no doubt that if M. Ferrier showed my letters to someone with the least familiarity with the Mathematics he would have easily understood how to measure the angle of refraction. And I would be very glad to know that master Ferrier or someone else is working to

[34]All of the above quotes from Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, pp. 186–87 (emphasis added).
[35]Ibid., p. 189.
[36]Ibid., p. 190.
[37]Haldane, *His Life and Times*, p. 124.
[38]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 228.

> put into execution the invention for lenses, and I would desire that they be successful.[39]

Descartes appeared to have lost any interest he ever had in monopolizing the project, and it would appear that he had a genuine desire to see it completed, by anyone.

Descartes' interest in the autumn of 1632 in the status of his aborted project is not difficult to situate biographically. It was during the summer of 1632 that he appears to have left Amsterdam for Deventer, there to be in proximity with his "friend and disciple Reneri" and to apply himself to *La Dioptrique*, which he intended to serve as a chapter of his magnum opus in progress, *Le Monde*, nearly completed by this time.[40] Back in Paris, it was Ferrier who spread the rumor that Descartes intended to publish, and it is difficult to say how he might have come up with the information, and, moreover, what prompted him to spread it abroad. Most probably he sought simply to give the impression that he was still close with his former master and knew of his designs.[41] Descartes instructed Mersenne to "assure everyone of the contrary and tell them I am doing nothing but learning to fence."[42] Ruses aside, it is likely that at this time Descartes was beginning to shape the final discourses of *La Dioptrique* around the same material that made up the two long letters to Ferrier in 1629. This decision almost certainly rekindled his commitment to the hyperbolic lens grinding machine.

In the winter of 1632 headiness about the new project seemed justified, yet by the winter of 1633 a precipitous shift in the intellectual climate compelled Descartes to leave *Le Monde* under wraps. Galileo had been called to Rome, and despite his powerful connections among the Jesuits and his personal friendship with Pope Urban VIII, *The Dialogue on the Two Chief World Systems* had been proscribed, and Galileo himself had been compelled to repent and recant the Copernicanism he avowed. This sequence of events rocked the scientific community to the northernmost regions of Europe and prompted Descartes to write Mersenne in November 1633: "I could not imagine that he, being Italian, and well liked by the Pope, from what I've heard, could be criminalized for anything else besides an effort to establish the movement of the earth. . . . " Perhaps that might earn him the

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[39]Ibid., p. 262.

[40]Reneri is alluded to this way in Haldane, *His Life and Times*, p. 153. On Descartes' progress on *Le Monde*, see Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 243.

[41]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 258.

[42]Ibid.

censure of a few cardinals, he went on, but if Galileo could actually be arrested in his old age then it seemed affirming Copernicanism could be safe nowhere. He continued, "[Copernicanism] is so intertwined with all the parts of my Treatise that I do not know how to separate it out," and for that reason all the promises that *Le Monde* would be forthcoming must now be forgotten.[43]

At the same time that Descartes decided to delay the release of his manuscript for *Le Monde* (later published in 1644), he elected to pursue sections from the work, which he promised in the same letter of November 1633 to send to Mersenne later. These sections (with additions) would be published in a single volume, in 1637, with the *Discourse on Method* as an introduction. *La Dioptrique* and *Les Météores* were the parts of *Le Monde* that could be presented without allusion to a Copernican universe, and by 1634 Descartes had already begun to circulate these treatises among his friends and colleagues.[44]

DESCARTES AND HUYGENS: THE PROJECT DEFERRED

The summer of 1635 found Descartes again at Deventer, this time with Hélène, a woman who bore him a child on the 18th of July. She was not the only new friend Descartes had made during his recent stays in Amsterdam. Jacob Golius, a professor of mathematics at the University of Leiden, had introduced Descartes to Constantijn Huygens. A diplomatic officer under Prince Frederick Henry of Orange (and knighted by King James I), a linguist, musician, and man of learning who had studied at Leiden, Oxford, and Cambridge, the elder Huygens quickly formed with Descartes a warm acquaintance.[45] Descartes soon passed a part of his manuscript on optics to Huygens, who by the 16th of April 1635 had decided to apply himself to the hyperbolic lens machine.[46]

It seems probable that in preparation for the publication of *La Dioptrique*, Descartes was intent on securing some success on the machine. His friend Golius reported discovering a lathe maker Descartes might visit to discuss the project, and about the same time Florimond De Beaune, a young and promising mathematician from the Touraine, began to express an interest in experimenting with the

[43]Ibid., p. 271.
[44]Ibid., pp. 315, 322.
[45]Roth, *Correspondence of Descartes*, p. xvii.
[46]Hashimoto ("Huygens, Dioptrics," pp. 54–56) treats some of this work, but the account is inaccurate in several areas (e.g., in praising the conception of the transverse lathe, so maligned by practical *optici*, as a "polishing procedure [that] gave the lens a shape and transparency much more perfect than could be attained without it").

construction of the device. De Beaune's devoted work on the machine would continue until 1640 when a piece of roughly shaped glass on which he was working cut his hand so badly that he was forced to abandon the project.[47] When he returned to lenses, years later, he spent more time on theory than on grinding.[48]

In October of 1635, Huygens, just home from a campaign, wrote Descartes that "my excitement to help realize the machine that you outlined for the grinding of the hyperbola has in no way cooled." On the contrary, Huygens had already put his own hand to the business of hyperbolic lenses, and after tracing by hand a hyperbolic curve with a fourteen-inch focal distance, he had sent the curve to a "Tourneur d'Amsterdam" who promised to make a standard forming pan from the tracing.[49]

Descartes applauded fourteen inches as a perfect experimental size, "extremely well chosen, because it is one of the largest that can be practically drawn without a machine and at the same time one of the smallest that can be used in a telescope that would be a little better than usual." In a courtly gesture of self-effacement, Descartes went on to defer with great flourish (and relatively little sincerity) to the challenge recently leveled by Martin Hortensius that spherical lenses were superior to hyperbolics:

> And so your work tracing a hyperbola is useless because the circular figure is the best, and there is plenty of reason to believe, concerning all this, the authority of a professor well versed in all the experience of artisans rather than the imaginings of a hermit who has never done any tests of anything he says.[50]

Descartes' breast-beating was ornament, but it serves as a reminder that not all the optical theorists of the day were persuaded that the hyperbola was the philosopher's stone of astronomy. This debate frequently broke down along the lines of craft lens makers versus those who placed their faith in the promise of theoretical demonstration. Descartes himself commented on the distinction between theory and practice, a gap he was ultimately unable to bridge: "I think I have written already everything I know about this: that is, that there is a difference between Theory and Practice such that the latter cannot attain to the perfection of the former. We must be content

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[47]Roth, *Correspondence of Descartes*, p. 132.
[48]For De Beaune on concave/convex lenses, see Adam and Tannery, *Oeuvres de Descartes*, Vol. 3, p. 286.
[49]Roth, *Correspondence of Descartes*, p. 4.
[50]Ibid., p. 6.

to approach perfection as closely as we can."[51] Descartes' frustrations with the limitations of handcraft ended up forming one of the primary motivations of his project to make lenses mechanically. His frustration with (as he saw it) unreliable and limited craftsmen (like Ferrier) increasingly compelled him to transform the project to make hyperbolic lenses from a project to build tools and devices to aid the craftsman into a project to build a mechanical system—the reification of a mathematical diagram—to replace the artisan altogether.

As far as Descartes was concerned, the spherical lens represented an approximation, in that over a small region the spherical curve of the lens "is not perceptibly different from a hyperbolic."[52] He went on to use this fact about limits to explain why larger lenses needed to be hyperbolic, implying that further advances in telescope power would necessitate lenses more hyperbolic in form.

Descartes' false modesty concerning the importance of the hyperbola did not deceive Huygens, who by December of 1635 had succeeded in having a hyperbolic lens turned by means of a hyperbolic forming pan. We have no drawings of the apparatus used by Huygens' turner, but it must have made use of a lathe to spin either the glass block or the form, because Huygens wrote Descartes when he sent him a sample: "I hope you will not find any of the faults ground into circles which you feared with the use of a lathe," alluding to Descartes' concern that using a lathe with a forming pan would turn any flaw in the pan into a circular gutter on the glass. Huygens' attempt to dispense with the complex hyperbolically edged grinding wheel, at least in the first attempts, was based on his concern that Descartes' device would be very difficult to realize: "coming out of the hands of the builder, I foresee mechanical problems [with your machine] even more significant than those of the lathe."[53] At the same time, the use of the lathe to shape a lens may have represented an adaptation of Descartes' system, and Huygens' modification (replacing the form wheel with a form pan) did not make the project seem any less outrageous to the community of trade lens grinders in Amsterdam: "And the lens makers," wrote Huygens tellingly, "having seen the cardboard model, dared to say that if it were realized they would be happy to eat the glass." Huygens refused to be discouraged, preferring to consider their mockery a symptom of panic in a profession about to be rendered obsolete by mechanical technology. In doing so he demonstrated his confidence

[51]Adam and Tannery, *Oeuvres de Descartes*, Vol. 3, p. 585.
[52]Ibid., p. 586.
[53]Roth, *Correspondence of Descartes*, p. 8.

in the machine-as-maker: "But it is in their interest to disparage the lathe which one day will ruin them."

Not any time soon, however. For when Descartes got a clear day on the 11th of December and tested the first effort of Huygens and his turner, the results were not encouraging. Using a piece of paper punched with small holes, Descartes observed the paths of narrow parallel light beams through the sample lens. He marked the focal distances of rays incident close to the periphery of the lens as well as those closer to the center and found that they did not coincide. Initially hopeful that the figure might still be hyperbolic and the problem lie in a miscalculation of the index of refraction for the piece of glass, Descartes did some calculations to see if any reasonable error in the index could account for the focal points he saw. Unable to demonstrate how anything but an error in the curve could account for the discrepancies, he wrote back to Huygens that the lens could not have a hyperbolic form.

Descartes closed the same letter with a warning about lathes that reveals more about the work Descartes did on the project while still in Paris:

> Then Monsieur Mydorge, whom I hold to be the most exact tracer of mathematical figures to be found, constructed the hyperbola that corresponded to the refraction of crystal on a true and well-polished sheet of brass, and with a compass with steel points as fine as needles, he then cut the hyperbola out of the brass plate and filed down the edge following the compass lines. And this brass hyperbola became the master from which an instrument maker named Ferrier cut on the lathe, a form, also of brass, carved out to the shape that was needed for the glass.[54]

What Descartes outlined was clearly a part of the earliest work he did on hyperbolics, before the development of the machine, when he was still in Paris and engaged with both Mydorge and Ferrier. Descartes went on to explain the difficulty that he and his collaborators had with this method, essentially the same as that which Huygens had used to produce his first lens. The rotational speed of the glass blank mounted on the lathe was found to differ too greatly from the edge to the center to achieve even grinding in the stationary form pan. Near the center there was hardly any cutting friction, while at the extremities of the lens-face the glass was ground away too fast.

[54]Ibid., p. 14.

Interestingly, in the same letter Descartes referred to the manuscript he sent to Huygens as "La Dioptrique," using this title for the first time.

This manuscript in the hands of Huygens seems to have been fully illustrated with drawings, for in June of 1636 Descartes requested that Huygens dig up the "figure of the machine for cutting lenses, which you allowed me to send you last summer," in order that the engraver from his printer might make a copy of it. In the same letter Descartes revealed the degree to which he had become engaged in hyperbolic lenses in preparation for the publication of *La Dioptrique*, clearly now well under way. "I send you a *chef d'oeuvre* of my hand," wrote Descartes as the salutation of the letter, "a model of a hyperbola, which you wanted me to have done by someone else . . . I have convinced myself that I did a pretty good job."[55] Descartes suggested that Huygens' turner apply himself to translating the template into a lens.

This second attempt using Descartes' tracing also failed, producing a lens Descartes criticized as "hardly more useful than the preceding one." This time, however, the cause of the mediocre performance was harder to specify:

> It is not that your turner has not given overall a figure sufficiently close to the model, as it [the lens] seems to assemble all of the rays at a focal point some 9 or 10 inches distant, and placing on top of it a card which has the shape of the model on it, I can see no other fault than that the middle is a tiny bit flatter than it should be.[56]

But that was not enough of a fault to explain why the "speculations in the 'Dioptrique' do not produce any of the effects for which you wait." Descartes ultimately found fault with the polish and suggested that Huygens try taking the lens to a "lunetier" for polishing, if he could avoid disturbing the shape. If that worked, Descartes promised a telescope that would be about half a foot in size (*largeur*) but that would be as powerful as the very largest.

Nothing more was mentioned of the suggestion to repolish the lens, and Descartes' attention at the end of 1636 and the beginning of 1637 was absorbed by the preparation for publication of the *Discours de la Méthode*, *La Dioptrique*, *Les Météores*, and *La Géométrie*. In June of 1637 the book appeared, and by the end of the summer Descartes had sent to a friend in Leiden to help Hélène and daughter Francine to join him near Alkmaar. By September, his correspondence reveals

[55]Ibid., p. 19.
[56]Ibid., p. 24.

that he was directing Huygens and the same turner in their effort to realize the recently published machine.

The extent to which Descartes had come to prefer the concept of mechanical making to craft practice over the ten years he had worked on the problems of lens grinding is reflected in an exchange concerning Huygens' turner, who had begun work on some version of Descartes' machine by September of 1637. Huygens reported to Descartes that the turner, "as he is a man industrious in the field of mechanical movements," had presumed to promise that he could "fulfill your intention [concerning the lenses] with much less complexity [*façon*]," exactly the sort of suggestion we might expect from a craftsman, to whom the overmechanization of Descartes' design would appear merely as a potential source of error (not to mention hassle).[57] Descartes' response is still more predictable. Instead of believing that less complexity was desirable, or even possible, he wrote, "on the contrary, I am persuaded that we must still add different things that I forgot."[58] Less mechanization was suspect, implying a greater reliance on the artisan's inscrutable, nonmathematical, and inadequately mechanical hand and eye.

Descartes' project to mechanize lens making was plagued by a set of problems that derived from the limitations of seventeenth-century machine tool technology. His idea of the machine could not be translated into a machine in the world because wood and horn and twine did not behave like the mental matter that Descartes set in motion in his mind. The attempts to produce lenses on a device like the lathe outlined in *La Dioptrique* were plagued above all by the tremendous difficulty of bringing two perpendicular, rotating axes into perfect alignment while providing a means to slide the spinning shaft of the glass blank forward as the glass was worn down by the grinding. Lenses often emerged with two centers, due to imperfections in this alignment.[59]

Moreover, despite the attention Descartes paid to shaping glass into a hyperbolic form, the production of successful hyperbolic lenses may actually have been blocked by the complexities involved in achieving a flat glass surface. As shown in Figure 18, the hyperbolic lens that solves the anaclastic for refraction must have a perfectly planar side, so as not to alter the parallel configuration of the arriving rays. Neither in the letters to Ferrier nor in *La Dioptrique* did Descartes

[57]Ibid., p. 55.
[58]Ibid., p. 59.
[59]Adam and Tannery, *Oeuvres de Descartes*, Vol. 2, p. 374.

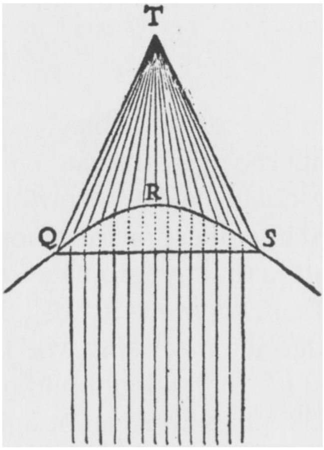

Figure 18 Plano-hyperbolic lens (Adam and Tannery, *Oeuvres de Descartes,* Vol. VI, p. 194)

address how this planar surface was to be realized. By 1641, the issue had been raised by none other than De Beaune, recovering from his injury. Descartes wrote Mersenne: "I am astonished by the difficulty he has with the flat side, because I believe that if the convex side were as accurately cut as the flat surface of an ordinary mirror we would have very excellent lenses."[60] Descartes may well have been astonished, but his astonishment did not make the task of achieving a truly accurate flat surface any easier. The shop technique for "stepping up" to a flat surface, which involved grinding three blocks in pairs until any two blocks appeared to share a perfectly flat side, was apparently unknown at the beginning of the century (at least in northern Europe), or perhaps Huygens and Descartes were merely unable to find anyone who would share such knowledge with them. Simply hand-rubbing the lens on a flat brass plate, as was probably done, did not deliver precise results.[61] By later in the century, it seems, this problem was more clearly understood, as demonstrated (elliptically) by this passage from a letter written by an Italian craftsman in 1672:

> and know also that in making a planar surface there is no way it can be perfected unless three of them are made at the same time and all

[60]Ibid., Vol. 3, p. 331.

[61]All the more surprising, in light of the difficulties experienced by De Beaune, are the results of modern optical testing on the plano-convex and plano-concave (spherical) lenses of two of Galileo's instruments: the flat sides of one objective and one ocular were found to be truly planar to a fraction of a wave. The two lenses were not, however, from the same tube. See Greco, Molesini, and Quercioli, "Modern Optical Testing," p. 117.

> most perfect, and this is enough to say to a great mathematician . . . Spherical [curves], either concave or convex are infinitely easier to make, while planes are much more difficult.[62]

Even if, by 1672, shop practices for achieving accurately planar glass were known, by this point the potential usefulness of hyperbolic lenses had been aggressively challenged by Newton's work on chromatic aberration, which called into question the amount of distortion caused by the spherical aberration that hyperbolics were intended to correct.

The publication of *La Dioptrique* in 1637 did more than motivate Huygens' turner to undertake a working wooden model of Descartes' machine in preparation for the task of building the full-scale apparatus.[63] By January of 1638, plans were afoot among Descartes' friends in Paris to have "Monsieur le Cardinal bring to perfection the invention concerning telescope glasses."[64] That cardinal was none other than Richelieu. The advantages of having Richelieu involved in the project went beyond his financial power. For anyone interested in publishing a treatise like *Le Monde* there would be a great deal of wisdom in engaging the interest of a reigning cleric like Richelieu. He could potentially afford a book with Copernican overtones exactly the protection it needed. For all that, Descartes did not seem overly enthusiastic about the efforts of Mersenne and des Argues to secure the cardinal's assistance, and he once again reflected concern about linking his scientific reputation to a workman: "Because he who works without my direction, whoever he is, will not, I believe, succeed on the first try, and perhaps to excuse himself will attribute the fault to me."[65]

Descartes' resistance to seeing an entirely new initiative undertaken in Paris may also be explained by the rapid progress reported by Huygens concerning his turner. By February of 1638 there was already talk of how to assure that the turner could secure an "octroi" in France, a royal prerogative entitling him to a monopoly on the Cartesian technology there.[66] By the middle of February the turner, who is never named and about whom we know very little, had completed the wooden model of the machine and presented it to Descartes

[62]Adam and Tannery, *Oeuvres de Descartes*, Vol. 3, p. 333. Letter from Burattini to Boulliau excerpted by Adam and Tannery from Libri, *Histoire des Sciences Mathématiques*, Vol. 1, pp. 218–28. There is also a discussion by Bolantio (circa 1660?) of making flat glass surfaces for lenses (in Bedini and Bennett, " 'Treatise on Optics'," p. 112). He does not, however, mention the three-plate technique.

[63]Roth, *Correspondence of Descartes*, p. 65.

[64]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 501.

[65]Ibid.

[66]Roth, *Correspondence of Descartes*, p. 65.

who came to see it. Descartes was so encouraged that he wrote Huygens that the turner "understands so well" all of the arrangements and measurements and was "so full of hope and desire to succeed, that provided he keeps working on it I cannot possibly doubt the project will meet with success."[67] Descartes reported further that the full-scale machine was to be made entirely out of brass and steel, and that this would delay its completion slightly. In the meantime, he wrote: "[the turner] says that he has learned that several others have the same plans as he has, and having cut some lens that gives them hope, they are preparing to demand an octroi from Dutch officials [*Msrs. Des Estats*]." For this reason Huygens was charged to block, to any legal degree, any efforts to secure an octroi on the part of another craftsman. The turner, like Ferrier, saw in the machine the opportunity for substantial revenue. Descartes, despite his early assertions about the productivity of the machine and his promises to Ferrier,[68] seemed much less persuaded about the commercial potential of the project in 1638 when he wrote to Mersenne:

> Concerning the glasses, I would not recommend that individuals invest in them, unless they want to buy them once they are made; and for me, I do not think that I will mix myself up in selling them: that is why I have had nothing to do with that, except that I help and encourage, as much as I can, those who want to work on them.[69]

Plunging ahead, hearing footsteps at his back, the turner appears to have completed the full-scale machine by December of 1638, when Descartes wrote to Huygens: "I think that you have been to see the turner of Amsterdam. I do not know what opinion you have of his glasses; for me, I do not find any faults besides the shape not being yet sufficiently exact, and they are not polished enough."[70] Clearly, the device was not fine-tuned yet, but as Descartes put it blithely, "it is a task that demands considerably more precision than cutting roses in ivory," doubtless referring to the turner's previous occupation. Still Descartes did "not despair that he will succeed with time," but pointed

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[67]Ibid., p. 70.

[68]In the notes of one seventeenth-century master lens maker it is recorded that he spent fifteen days working on a single objective lens (Adrian Auzout writing in 1664, cited in McKeon, "Adrian Auzout"). In an effort to encourage Ferrier to work on the hyperbolic lens grinding machine, Descartes wrote that once the system had been initialized and adjusted "each lens may be cut in a quarter of an hour," clear evidence of his conception of an automatic production system.

[69]Adam and Tannery, *Oeuvres de Descartes*, Vol. 2, p. 389.

[70]Roth, *Correspondence of Descartes*, p. 87.

out that he would do well to succeed sooner rather than later, since rumors had come to Descartes' attention that the hyperbolic machine had been realized in Naples. In the same year that the lens making of Neapolitan Francesco Fontana had challenged the primacy of the Florentine masters, a threat from the city on the bay could not be ignored.[71] When in February of the following year a telescope brought from Naples made the rounds in Paris and caused a stir, Descartes was quick to surmise, just from a written description, that its objective lens was hyperbolic.[72]

The best summary of the work by the turner comes in a letter from Descartes to Ferrier in September of 1639.[73] Acknowledging an unsolicited letter from Ferrier on his recent progress, Descartes offered a reply in kind, explaining in detail the successes and difficulties of the turner. Although the hyperbolic cutter worked well, the impasse reached by the turner involved the lathe and the shaping wheel, which generated irregular lenses, often with two centers.[74] Descartes claimed that part of the problem lay in the way the turner designed the wheel, a wooden core with brass plating at the circumference (which held the hyperbolic groove). The wooden core expanded and contracted with humidity changes and distorted the shaping edge. Since the completion of the machine, Descartes wrote, the turner had brought him two or three lenses that had seemed promising but "they were so full of imperfections and badly polished" that when stopped down to the aperture of ordinary telescope lenses they were not even transparent. When completely exposed they "had the same effect as an ordinary lens, which shows that if they were well polished they would have the same effects as larger lenses."[75] Descartes revealed in closing that the turner's interest seemed to have waned since the completion of the machine and that "he worked very little during the winter, and that the man who employed him left Amsterdam at the beginning of the summer." We must assume that this is a reference to Huygens, who, though he actually resided in the Hague, did effectively leave

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[71]Bonelli and Van Helden, "Divini and Campani," p. 5.

[72]Adam and Tannery, *Oeuvres de Descartes*, Vol. 2, p. 513. The excellence of this telescope can be attributed to the excellence of the Italian-ground objective or to the configuration of lenses in the compound eyepiece, a technique on which the Italians were more advanced than the French in the late 1630s.

[73] We can be assured that the letter should be dated September 1639, and not September 1638 (as it is labeled by Adam and Tannery), by a reference to the machine completed by the turner "a year ago." We know from the Huygens' correspondence that the turner did not complete the full-scale machine until 1638. Adam and Tannery express some reservations about the date they suggest.

[74]Adam and Tannery, *Oeuvres de Descartes*, Vol. 2, p. 374.

[75]Ibid., p. 375.

Holland in the summers of both 1638 and 1639. Descartes closed the letter with politeness that can only be considered saccharine in light of the long silence between the two men and the threat of legal process that had culminated their last communication. Despite recently having written to Mersenne that Ferrier's work "is a great show that will come to nothing," Descartes concluded with words of effusive praise for his on-again, off-again artisan: "what you have sent me makes me want not to encourage these others to pursue the task, because if someone in the world can bring the project to completion I doubt not at all that it would be you."[76] Considering that Ferrier had brought nothing to completion in recent memory, it does not seem odd to discover that this letter represents the last extant exchange between the men, and no further references to Ferrier appear in the remaining three volumes of Descartes' correspondence.

The turner, too, fades from the historical record at the end of the 1630s. We can imagine that Huygens' frequent political and military travel prevented him from being present to direct and encourage the craftsman. The last mentions of the turner relate to an apparently unsuccessful effort in 1640 to help him secure some unspecified "position" in the town of Leiden.[77]

In the turner, Descartes had had a craftsman not unlike Ferrier, with the exception of the former's greatly improved productivity. Though neither appears to have had much experience working with glass, each possessed applicable technical skills—Ferrier more in mathematical instrumentation, and the turner more in lathe work. When it came to the more sophisticated geometry embedded in the machine, however, these men had little to offer. Only in Florimond De Beaune did technical proficiency combine with a superb grasp of mathematics and a passionate commitment to hyperbolic lenses. Because of De Beaune's increasing attention to the project, it is not difficult to understand Descartes' relative lack of concern for the waning interest of the "Tourneur d'Amsterdam."

[76]Shea's interpretations of Descartes' words as somehow a "vindication" of the craftsman (*Magic of Numbers*, pp. 200–201) or as a "touching recognition of the skill of the artisan" ("Descartes and the French Artisan," p. 159) are thus, on my reading of these materials, very much mistaken.

[77]Huygens wrote Descartes (from "a tent buffeted by a great storm of rain and wind" at the camp of Reeck, where he was serving in the army of the Prince of Orange) that despite the momentous events afoot and the preparations for war, he had found the time while still in the Hague to secure a letter of support for the turner from a high-ranking official. Having hand-delivered the letter he hoped it would have "the promised effect." (Roth, *Correspondence of Descartes*, p. 133). Descartes wrote back that he appreciated his friend's effort, but the outlook did not seem hopeful. From these exchanges it seems clear that the turner had stopped work on the machine but that he had remained on excellent terms with his masters.

From a letter written to Roberval by De Beaune himself, we know that as early as 1638 De Beaune had done experiments with glass wedges to corroborate empirically Descartes' geometrical method for establishing refractive indices. Moreover, in the same letter he wrote that this demonstration: "motivates me to undertake making the glasses this spring at the latest, and I will make the necessary machines this summer."[78] By March of 1639 he was working so intensely on the hyperbolic lenses that he had "practically no leisure to occupy myself with other things."[79] Descartes appears to have been impressed with the young man's work, because he wrote him at this time: "I do not have anything to say concerning what you think it wise to change on my machine for making glasses, because these are things that you can judge better than I."[80] Further indications of De Beaune's grasp of Descartes' intentions are offered by letters written in the summer of 1639, in which Descartes discussed developments made by De Beaune on the geometry of *La Dioptrique*.[81] When the mathematician Pierre Petit composed a treatise against *La Dioptrique* in 1639, Descartes opted to defer his defense to De Beaune, writing: "I see so much ability and integrity in M. De Beaune that I am ready to subscribe to all that he judges."

By January of 1640 Descartes wrote Mersenne that all hope for the lenses rested in the outcome of De Beaune's work.[82] And Descartes' assertion seems justified, in that De Beaune's serious injury just two months later (while working, recall, on a sharp piece of unformed glass) appears to have sounded the death knell of Descartes' involvement with hyperbolic lens grinding. Descartes wrote Huygens concerning the accident: "In the long term he cannot continue work, which seems to mean, speaking frankly, that he cannot complete the project." Did this failure of what seemed to be the project's last hope dishearten Descartes? Apparently not. Rather, it seems to have swelled his pride in the unsullied conceptual purity of his system. The idea of the machine had transcended its mechanics: "Do you think I am sad?" he wrote Mersenne shortly after hearing the news, "I swear to you that, on the contrary, I discern, in the very failure of the hands of the best workers, just how far my reasoning has reached."[83]

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[78]Adam and Tannery, *Oeuvres de Descartes*, Vol. 5, p. 518.

[79]Ibid., p. 539.

[80]Ibid., Vol. 2, p. 512; it should be noted that Descartes would never have addressed Ferrier in a comparable manner.

[81]Ibid., p. 562.

[82]Ibid., Vol. 3, p. 9.

[83]Because one close reader offered a variant translation of this passage, I will give the original here: "Vous pensez peutestre que i'en sois triste? et ie vous iure que tout au contraire ie veux tirer de la vanité de ce que la main des meilleurs ouuriers ne peut attaindre où mon raisonnement est paruenu." Roth, *Correspondence of Descartes*, p. 131.

3

A Twin Legacy: Hyperbolic Lenses and Mechanical Makers

IN THE WAKE OF PUBLICATION

The circulation of *La Dioptrique* introduced the educated and technical communities of Europe to the promise of the hyperbolic lens, as well as to the promise of machine-made lenses, and a number of savants and artisans took up the task of trying to make a hyperbolic lens, either by machine or by hand. Others began to experiment with a variety of mechanical devices and systems to aid in the making of spherical lenses. It is more difficult to discover the nature and progress of lens making projects taken up by artisans, because in the majority of cases they did not publish their results and often guarded their innovations and techniques as trade secrets. Published works after 1637, however, provide excellent evidence that natural philosophers and active astronomers were preoccupied by mechanical systems for the production of lenses for telescopes. As I have suggested, none of these systems succeeded in making lenses, either spherical or hyperbolic, that were comparable to the handcraft techniques of the master Italian lens makers and those who emulated them. The enduring promise of mechanized systems, in the absence of any concrete success, serves as a testimony to the power of the idea and the ideal of the machine in the elite circles of seventeenth-century science. Moreover, I believe the preoccupation with mechanical devices for lens making subtly betrays tensions in the emergent relationship between speculative natural philosophers and craftsmen, itself a result of collaborations on devices like telescopes, air pumps, and the other new

instruments of scientific investigation. The project of displacing the artisan by building machines to ensure the excellence of lenses and telescopes (regardless of the manual skill of the craftsman) strongly suggests an impulse on the part of a number of natural philosophers to distinguish the instrument of scientific investigation from the traditions of practical instrument-devices from which it arose. By mechanizing the system for making the crucial components of optical instruments, natural philosophers were working to free their pursuit of truth-seeking instruments from dependence on the vagaries of handcraft. Descartes' frustration with craftsmen by the end of his life went beyond disappointment with the limitations of their craft, to a bitterness reflected in his complaints to his correspondents about the extravagant sums that lens grinders garnered for their inadequate labor.[1] Other natural philosophers delivered even more scathing assaults on the character and ability of the optical craftsman.

I turn now to accounts of several important mechanical lens making systems that received attention after the publication of *La Dioptrique*.

RHEITA

Anton Maria Schyrleus de Rheita, a Capuchin astronomer of Bohemia, brought forward in 1645 a quirky book of astronomy entitled *Oculus Enoch et Eliae*.[2] Among the "useful and happy works" heralded by this text was an ingenious mechanical system for producing the new hyperbolic lenses.[3] Despite an avowed anti-Copernicanism and a facility for interlacing scripture and astronomy, messianic visions and physical optics, Rheita was not at all peripheral to the community of astronomer-savants of Belgium and Holland, even if he was perhaps eccentric to it. The striking title of his major work reflected his faith that the new optical devices were prophetic instruments, engaged, like the ancient prophets Enoch and Elijah, in a life and death struggle with the devil himself. A student of Gutschoven, who had studied mathematics and optics with Descartes, Rheita went on to become the instructor of Johann Weisel, who would become one of the better-known lens makers outside of Italy.[4] Rheita himself is often credited with the discovery of the terrestrial telescope, made out of four convex lenses and featuring an erector lens to right the inverted image of an

[1]Roth, *Correspondence of Descartes*, p. 161, and again p. 314.
[2]On Rheita see Bedini, "Tube of Long Vision"; and Thewes, *Oculus Enoch . . . Ein Beitrag.*
[3]For a discussion of the device, see Goercke, "Der Schliff aspharischer."
[4]Bonelli and Van Helden, "Divini and Campani," p. 8.

astronomical telescope,[5] and Rheita's familiarity with the craft of lens making is demonstrated in his ciphered reference to a new technique for polishing spherical lenses using sheets of blotter paper treated with emery and shaped wet to fit the lens.[6] This technique is referred to in later works and was part of the craft practice of Campani and Cherubin D'Orleans later in the century, but Rheita's reference appears to be the first.

Rheita did not allow his knowledge of the subtleties of the handcraft in lens making to interfere with his mechanical vision in his design of the "new and most easy machine for the preparation of a hyperbolic form, exactly made according to the true proportion of refraction of any glass." This technique (Figure 19) demands at least two devices that, taken together, work not unlike the integrated system of Descartes: one device (number 2, on the left) shapes a steel plate into a hyperbola; another device uses that hyperbolic blade to cut a grinding form (either a wheel, as in the device numbered 3, or a slot, as in the device numbered 4). Rheita's system was intended to work on a more manageable scale than that of Descartes, as the scale of 25 "pouces" in the center illustrates, and though it is not as compounded and automatic a mechanism as the lens making system in *La Dioptrique*, it clearly was designed to inspire the reader with a vision of producing hyperbolic lenses by the turn of a crank. Although the system for transferring the hyperbolic plate onto a grinding surface and then onto the lens appears about as unworkable as that of Descartes, Rheita does include several elements Descartes omitted, such as a means of putting pressure on the lens as it was being worked (number 3, letter u) and a set of drive wheels of different diameters so that the lens could be driven at different speeds on the plate. Unlike Descartes, Rheita did not design his system in such a way as to be self-regulating, and the grinding wheel is not constantly being returned to the hyperbolic form.

The most noteworthy component of Rheita's system was his technique for shaping the hyperbolic plate. The box labeled 2 was punched with a set of peg holes radiating from the center slot. The angle-bar srq (labeled number 5) was to slide against two pegs placed in opposing holes on the box in such a way that the vertex of angle-bar srq

[5]Van Helden, "Telescope in the Seventeenth Century," p. 44.

[6]The cipher appears on page 344 of *Oculus Enoch et Eliae*, and reads "Cphaatritnaæ lpeunlimsesnitmoo iangggelnuitoisnea turiitproulmi pionleiato &c." Reading the odd-numbered and even-numbered letters of each code word separately, the passage reads, "Charta patinae lenissimo pulmento ingeniose agglutina tripoli vitrum polit in ea," or "he polishes the lens perfectly thus, by means of finely powdered tripoli, with paper pasted into the forming pan."

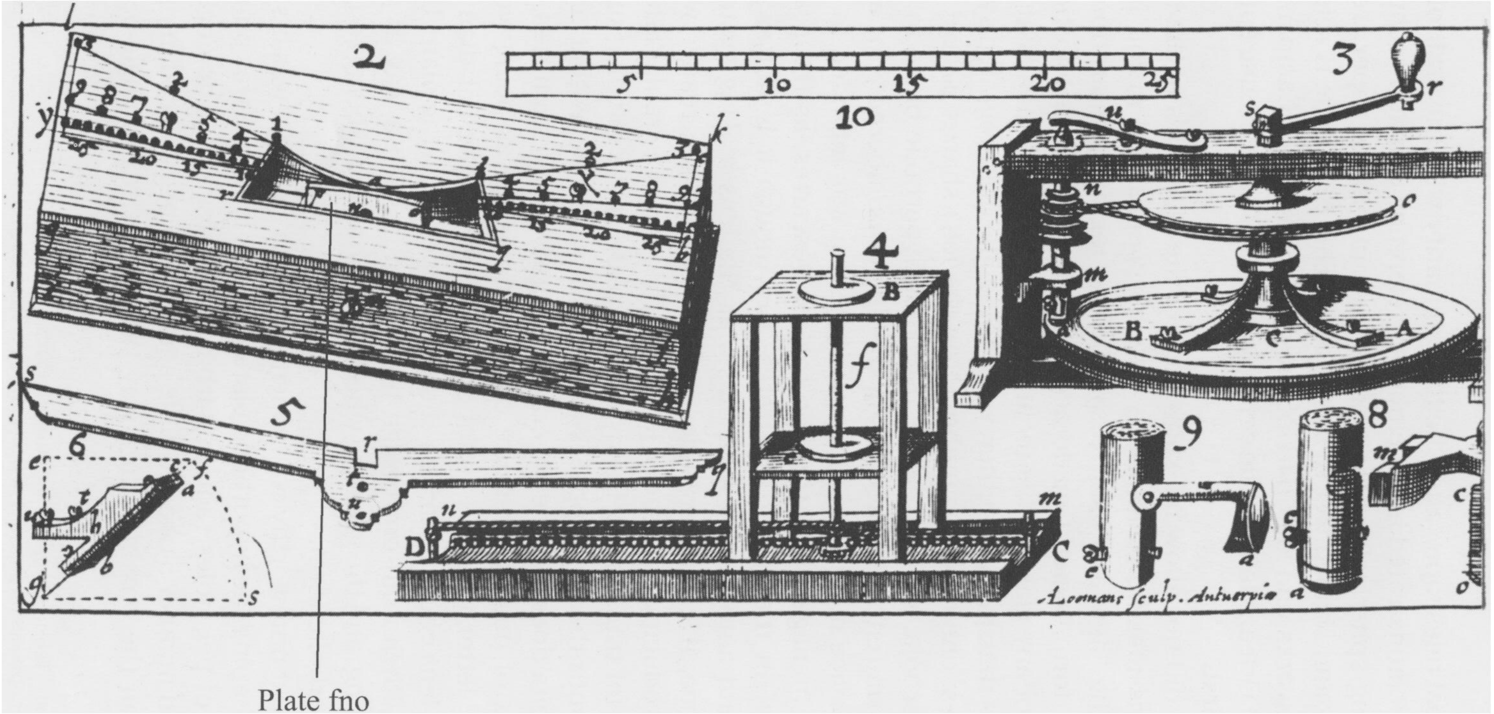

Figure 19 Rheita's machines (Rheita, *Oculus Enoch et Eliae*, after page 349)

traces the arc of a circle.[7] An angled file (number 6) is attached to the bent bar srq at the vertex r, and placed at an angle with respect to the plane of the angle-bar. As the vertex r traces the arc of a circle in the plane of the box, the angled file scribes a segment of a cone. Intersecting this cone (and fixed in such a way as to be perpendicular to the surface of the box, and thus parallel to the axis of the cone) sits the metal plate labeled fno, which is positioned in the slot in the middle of the box. The top edge of this plate is thus ground to a hyperbola by the motion of the angle-bar srq back and forth against the pegs placed in the pegboard on the box top.

This clever device, based on a similar principle to that of Descartes' machine but realizing the hyperbola by a different mechanism, was not seized on by contemporaries. Whether this was due to the somewhat mystical character of the book, or perhaps its limited circulation, is difficult to gauge. The device as a whole appears impractical in several ways, but hardly less practical than the mechanical systems of several contemporaries. Notably, Rheita's system does appear to demonstrate a preoccupation with shop details, and it is outlined in such a way as to evince the importance of artisanal skill. For instance, the device for shaping the hyperbolic form is not a large automatic machine but rather a workable tool for guiding the hand of the craftsman. Although Huygens and others knew of Rheita's book, I know of no evidence that anyone ever attempted to realize his device. Shortly after the publication of *Oculus Enoch et Eliae*, Rheita left Bohemia for Italy and little is known about where he was or what he did in the years before his death in 1660 in Ravenna.

There is some evidence that he continued to interact with lens makers, for a manuscript on lens making from Florence (which probably dates from the 1650s) mentions Rheita's name beside that of Descartes and identifies them as the two men "responsible for instruments for hyperbolic lenses." The manuscript is an unusual one in that it provides evidence for how craft-oriented lens makers responded to the theoretical promise of hyperbolic lenses. Writing of the hyperbolic lens making machines, the author stated simply in Italian, "We do not know if they work," and he went on to identify the difficulty of transferring the form to the lens by means of a lathe with two perpendicular rotating shafts. Though the provenance of the manuscript is

[7]Proposition 25 of Book 3 of Euclid.

unknown, the use of Italian and the absence of mathematics suggest a writer closer to craft traditions than to abstract optical theory, and the singular recommendation the author makes concerning the manufacture of hyperbolic lenses exemplifies the kind of craft approximation that could be proposed in place of a rigorous mathematical and/or elaborately mechanical system.[8] The writer pointed out that lathes easily slip out of alignment, and therefore he advocated grinding hyperbolic lenses in pans like those used for spherical lenses. He claimed (Figure 20) that by fixing a shaft in such a way that it followed a spherical template at one end (here shown at the top, ABILC), the other end could be used to shape a "hyperbolic" grinding pan (shown below, DNMF). The result of this operation is not actually a hyperbola along the curve DNMF, but rather the base of a teardrop-shaped curve that would now be represented by a higher-order polynomial. In this sense, then, the design for this hyperbolic lens making device is fundamentally flawed, yet it nevertheless offers an interesting example of how a craftsman without much (if any) mathematical training might seek to approximate by hand a curve he knew to be slightly more conical than an ordinary lens shape.

It is perhaps worth noting here that craft approximations of hyperbolics were tried by others as well. In his *Machina Coelestis* of 1673, Hevelius took all of chapter 23 to explain his attempts at fashioning hyperbolic lenses. He claimed to have developed a new way to achieve hyperbolic metal plates by using an ordinary woodworking lathe to turn a large wooden cone from a block of wood pieced together in such a way as to contain a sheet of metal parallel to the axis of the cone (although this same method is earlier credited to T. B. Mocchi, son of an Italian sculptor, who had settled in Paris as a "polisseur de verres").[9] Although this technique did indeed provide Hevelius with geometrically accurate hyperbolic plates, he admitted that he had been unable to transfer the curve to a forming pan or a lens. As a result of these failures, he settled on a method of rotating a glass blank mounted at an angle against an ordinary spherical forming pan (Figure 21), producing a more or less "conical" lens depending on the configuration of the device. The curve of this lens, as best I can make out, is actually nothing more than two arcs of a circle smoothed over at their point of intersection, but Hevelius claimed to have used this

[8]Torricelli, "Breve Trattato intorno," Biblioteca Nazionale Centrale, Florence, Pal. 1130. I thank Albert Van Helden for directing me to this manuscript.

[9]Huygens, *Oeuvres*, Vol. 1, p. 385.

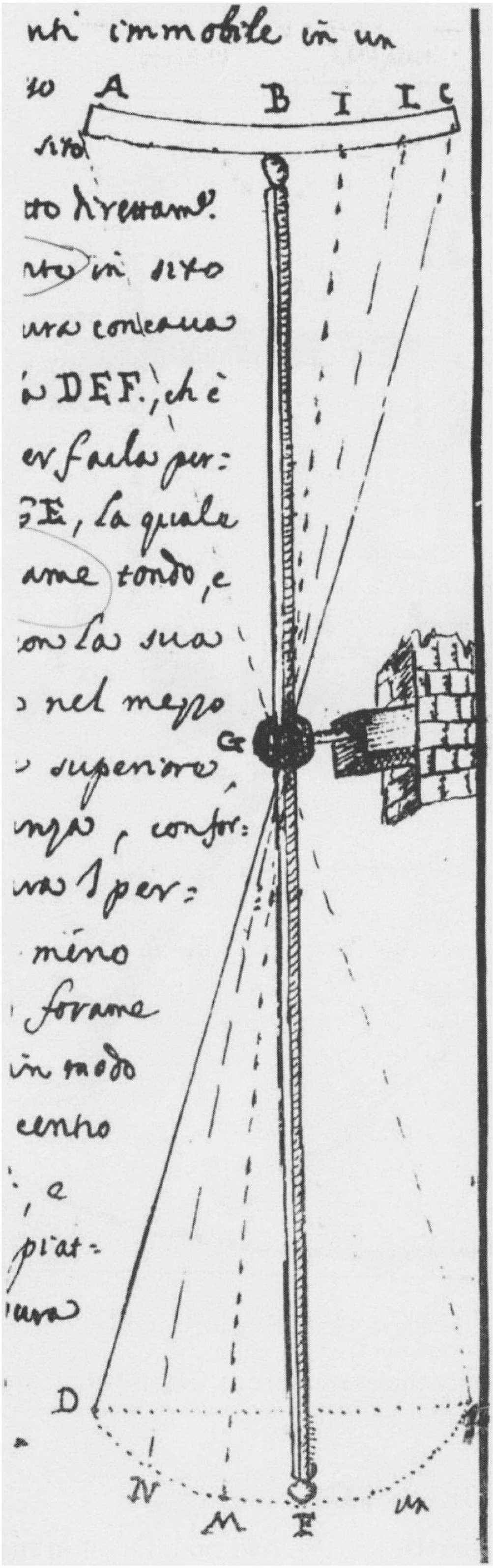

Figure 20 Toricelli's device (Toricelli, "Breve Trattato," opposite p. 82)

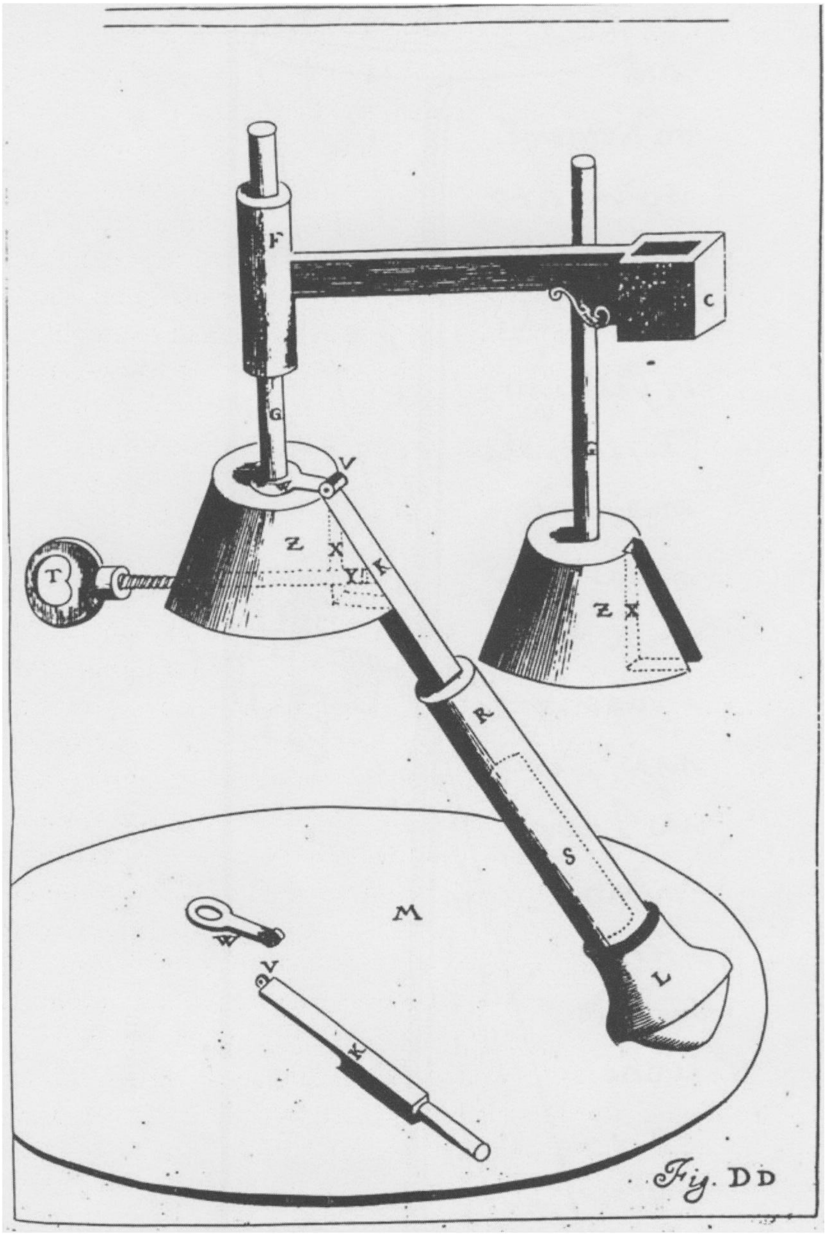

Figure 21 Hevelius' shop technique (Hevelius, *Machina Coelestis,* after page 433)

method to "successfully make numerous lenses" that were "far superior to lenses of spherical sections."

MAIGNAN AND BRESSIEUX

Emmanuel Maignan, like Descartes, had no interest in the promise of craft solutions to the problems of lens making in general, and was

particularly interested in mechanizing the production of aspherical lenses. Writing in 1648, in his magnum opus, the *Perspectiva Horaria,* Maignan stated that the object of his lens grinding device was to "delineate a hyperbola not less exactly than a compass describes a circle."[10] Maignan, a theologian as well as natural philosopher, was a Minim friar who lived in Rome from 1636 to 1650 and worked in a circle of savants who experimented with creating a void.[11] His exhaustive *Perspectiva Horaria,* dedicated in large part to the construction and analysis of sundials, demonstrates the extent of his familiarity with precision instrumentation. In several ways Maignan exemplifies the new relationship between philosophy and the arts in the seventeenth century. He was a professor of philosophy and theology at the convent of Monte Pincio in Rome, well trained in both scholastic thought and the new Cartesian philosophy, yet critical of both. His interest in the practical and mechanical arts was part of a broader effort to introduce experimentalism into scholastic thought. In the work of such a thinker, especially one who spent time in Italy, we might expect to find a particular sensitivity to the subtleties of handcraft and an awareness of the benefits to be derived from careful collaborations between philosophers and artisans. Instead, Maignan's machines betray a systematic project to generate complex lens making systems—for both spherical and hyperbolic productions—that could replace the artisan.

Having outlined the lens problems that beset the best telescopes, Maignan introduced his lens grinding machines with a promise that they would end the natural philosopher's dependence on the craftsman: "I will thus bring forth a most certain solution to this unfavorable situation, in the following propositions, so that [a lens] may be produced easily enough and not less excellently by a hand of indifferent accuracy."[12] Maignan listed the great lens makers who were his contemporaries, as well as their predecessors, and in doing so he demonstrated his familiarity with the established traditions of craft practice. Yet even though he claimed (elegantly) that "the hand of Divini is guided by divine grace," the hand of future artisans, he promised, would be directed by machines.

Maignan provided the designs for three machines in his text. Figure 22 represents his vertical lathe for cutting spherical forms, a version of a tool that was actually used by lens craftsmen to shape accurately the concave forming pans in which convex lenses were

[10]Maignan, *Perspectiva Horaria*, p. 700.

[11]Gillispie, *Dictionary of Scientific Biography*, s.v. "Maignan." See also Louyat, "Emmanuel Maignan"; and Rosenfield, "Peripatetic Adversaries," pp. 23, 37. See also the entry on Maignan in Bayle's *Dictionnaire Historique*.

[12]Maignan, *Perspectiva Horaria*, p. 687.

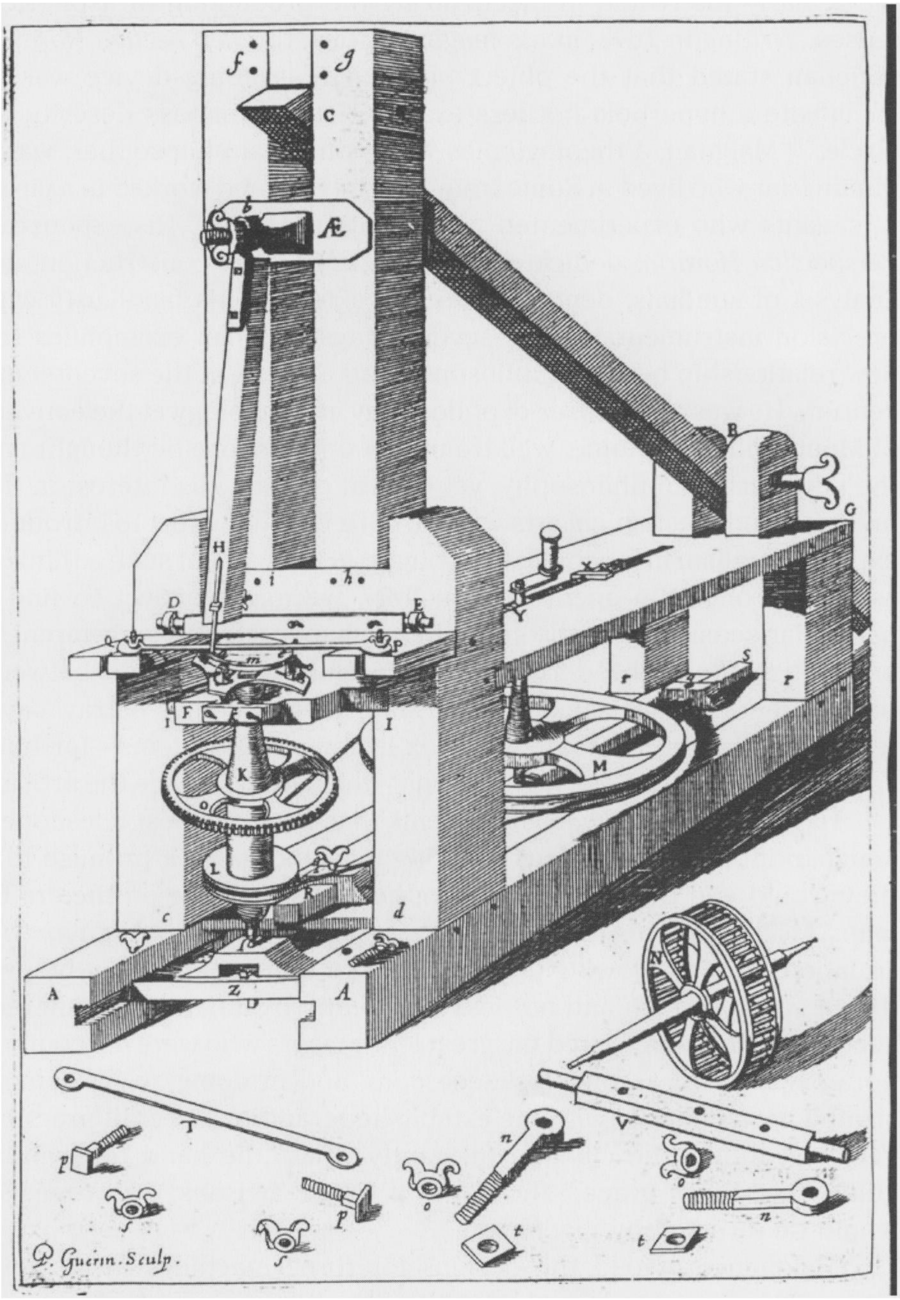

Figure 22 Maignan's concave form lathe (Maignan, *Perspectiva Horaria*, prop. LXX)

ground. Figure 23 represents a more complex version of the same kind of lathe, constructed in such a way as to produce convex forming plates that could be used to grind concave lenses. Then, after a brief recapitulation of Descartes' work on the construction of the hyperbola suitable to the refractive index of a given piece of glass, Maignan presented his own version of Descartes' machine (Figure 24). Maignan was clearly a believer in the promise of the hyperbolic lens and, like many of his contemporaries, felt that progress in the science of astronomy was being retarded by inept craft practices that were difficult to elevate to the plane of theory:

> As for what touches on theory, nothing more can be added to that which the preeminent Descartes brought to light in his "Dioptrics," whence it is shown what new perfections the hyperbolic or elliptical lens may bring to the telescope, far exceeding that which we have out of spherical lenses worked as well as possible. When it comes to practical demonstrations, though, truly I have not seen until now anyone of undisputed integrity bring forth anything certain, either concerning the construction of the form, or (what is of greatest moment) concerning the art of perfect polishing of these lenses.[13]

Despite his fascination with the theoretical promise of the mechanical philosophy, Maignan was not merely a bookish scholar, but was actively engaged in both lens making and the making of machines to make lenses. Carlo Antonio Manzini, the author of an Italian handbook on lens craft, *L'Occhiale all'Occhio Dioptrice Practica*, who had seen the secrets of Campani's workshop and written about optical lathes, is reported to have said on seeing Maignan's workshop in 1662 that his methods for making forms were "the best and surest to have been invented."[14]

Maignan's hyperbolic machine prepares a form not unlike that of Rheita (of whose work he claimed to think little), in that the hyperbola is cut into a circular channel in the face of a spinning brass or steel plate (f in the diagram, as highlighted in my annotations). Maignan's device, however, is more "automatic" than Rheita's, in that the mathematical part of Maignan's machine—the part that generates the hyperbolic line—cuts the shaping pan directly, whereas in Rheita's system a second mechanism was required to transfer the hyperbolic plate to the shaping wheel. At the same time Maignan's system is *less* automatic than that of Descartes in that it does not also provide for the grinding

[13] Ibid., p. 688.
[14] Huygens, *Oeuvres*, Vol. 4, p. 48.

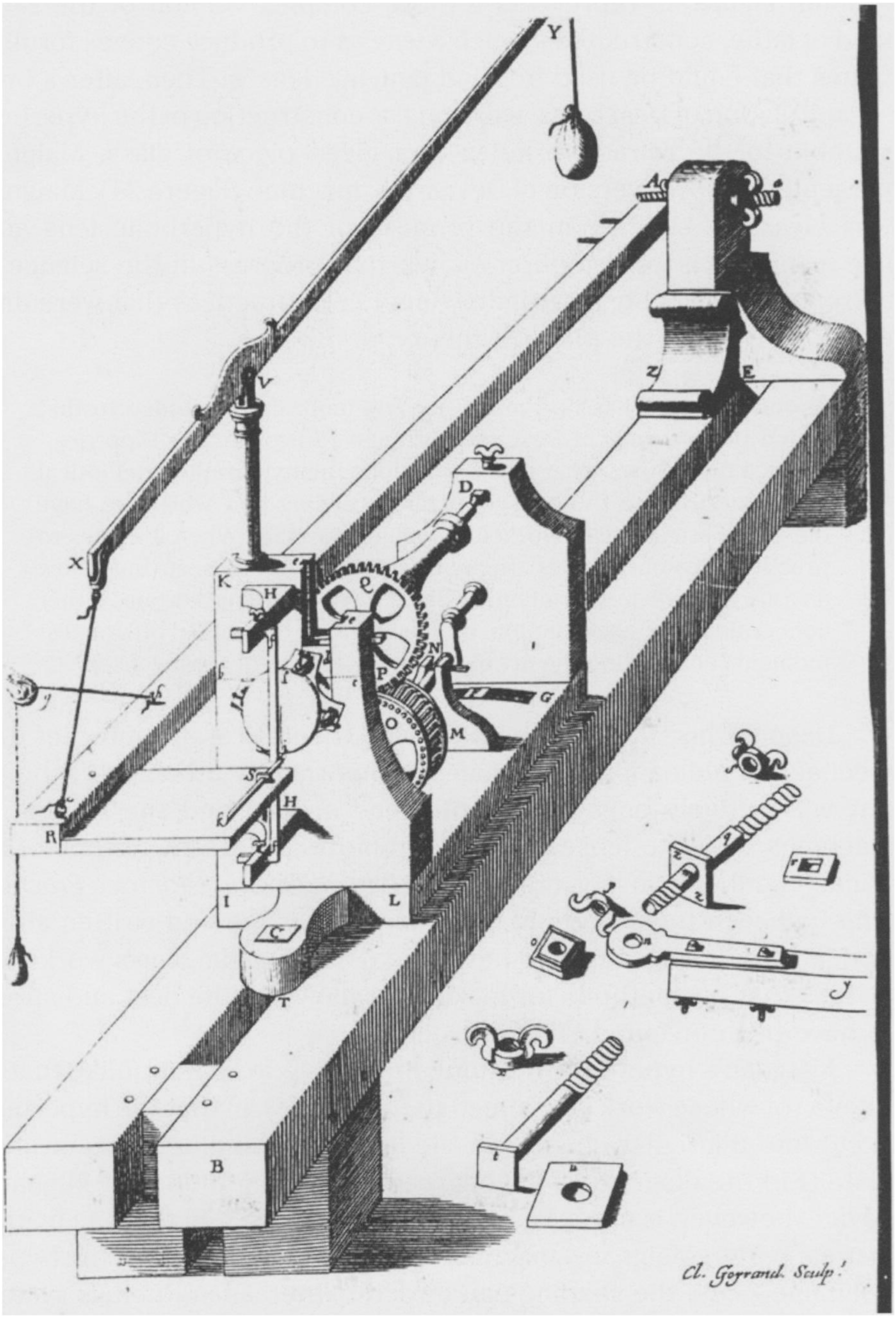

Figure 23 Maignan's convex form lathe (Maignan, *Perspectiva Horaria*, prop. LXXI)

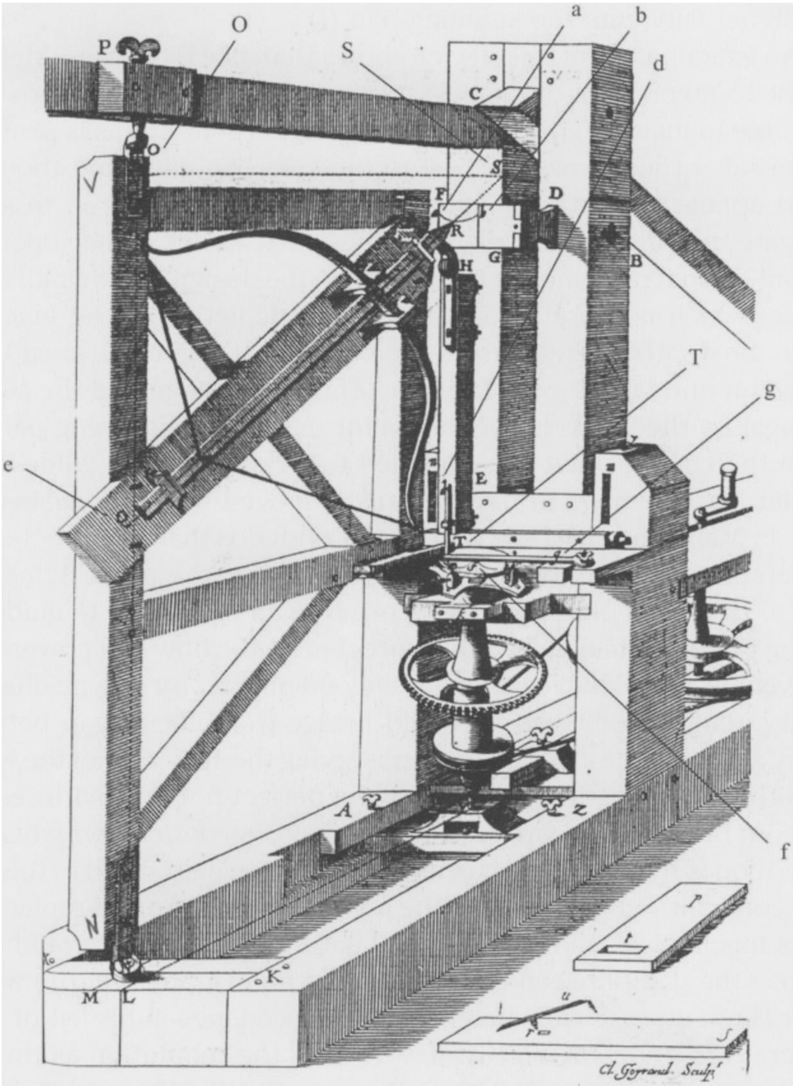

Figure 24 Maignan's hyperbolic machine (Maignan, *Perspectiva Horaria*, prop. LXXIII)

of the lens as part of the same machine. In fact, no reference is made in Maignan's text as to how a lens is to be shaped in his hyperbolic form.

To understand the mechanism of Maignan's device it helps to think of Descartes' machine turned on one end, in such a way that a cone is described by OeS when the "gate" NVF swings at the pivot points P and L. The bar HE hangs parallel to NV (the axis of the cone) and is hinged in such a way as to follow, pantograph-like, the motion of the "arrowhead" stylus R, as it scribes a hyperbola (ab) on the

plate G. A chisel tip (d) attached at the bottom end of the hanging bar HE actually cuts the spinning pan (f).

An examination of this device shows that, like Descartes, Maignan sought to mechanize the necessary processes as much as possible. The force to maintain the position of the hyperbolic stylus is provided by the salient longbow attached to the swinging gate, and though it would appear that at least one artisan would be required to swing that gate, no provision is made in the illustration for that operator. The only visual reference to the artisan in the design is the small crank handle, which is literally marginal to the depiction of the machine.

In most lathe designs from the seventeenth century, even those for use on optical projects, the hand of the artisan guided the cutting tool against the work. In the lathes for cutting lens-shaping pans, in which the cutting point was attached to a radius arm to guide it in a circular line, the hand of the artisan still moved the point against the work. In Maignan's machine there is no evidence that he expected the workers' hands to touch the cutting arm HE or the point d. Instead, a set of rests and plates (g and T) are provided in order to guide the cutting point mechanically as it is directed by the bow and powered by an invisible technician swinging the wooden gate. By this mechanical rigidity Maignan believed he could bridge the difficult gap between theory and practice: "In sum then, observing the structure of the whole machine, it is clear that its work will be perfect not only with respect to theory but also in regard to practice, since, *by construction*, wherever the motion is free and easy it is most entirely regulated and in this way most constant."[15] By distancing the hand of the artisan and replacing it with a mechanism, the experimental natural philosopher could hope to close the gap between the mechanical philosophy and the world.

It is not strange that Maignan gave precedence in his list of great lens crafters to Eustachio Divini, who held the reputation as the premier lens maker in Europe from the end of the 1640s until the early 1660s, when the meteoric rise of Giuseppe Campani eclipsed his success and established a new standard in spherical lenses. During the 1650s in northern Europe, Huygens in Holland and Auzout in France both worked to perfect lenses and compared their work to the acknowledged Italian masters. Two letters from Henry Oldenburg, visiting Paris in 1659, indicate that efforts to grind lenses with machines, particularly hyperbolic lenses, still captured the minds of European savants during this very period when Italian handcraft had come to epitomize the practice of lens making:

[15]Maignan, *Perspectiva Horaria*, p. 700.

> We have seen this morning Monsr. Bressieux, a great artist for working Hyperbolical glasses, & ye Machines wch he hath in a manner ready to begin to worke. If ye practice prove as easie, as ye demonstration is said to be cleere, I doe not doubt we shall be made more acquainted with ye celestial bodies, than hitherto we have been.[16]

It is not impossible to imagine that French, English, and Dutch projects to mechanize lens making were, at least in part, the northern European response to the superiority of the Italian lens craft. The machine promised to allow the savants of France and England to possess instruments as good as or better than those made by Divini and others, without the expense and inconvenience of importing them.

Later in 1659, Oldenburg wrote on behalf of Bressieux to request that several pieces of glass be sent from England, the glass production of Venice having lapsed in quality, in order that Bressieux might begin to put his machines to the test: "He hath in a manner ready 7. Machines for both hyperbolicall and Sphericall glasses; & he carried us to his lodging to see them. Where he showed us three Machines for concave hyperbolicall, three others for convexe hyperbolicall, & one more for to work ye sphericall glasses with more exactness yn thitherto."[17] Though there is no evidence that anything ever came of Bressieux's work, and there are no specific descriptions of his devices, there is good reason to believe that he was one of several instrument makers in Paris at that time working on Descartes' system. Bressieux even claimed to have been a student of the master before his death, though there is no mention of him in Descartes' correspondence: "I have told Mr. Jones also, that this Bressieux is the very workman that did work for Des Cartes for two whole years."[18]

When word reached northern Europe in the early 1660s that the lenses of Divini had been surpassed by the work of a team of upstart brothers, Giuseppe and Matteo Campani, it came attached to a rumor that the Campanis had perfected a mechanical system for shaping lenses directly on the lathe without the use of a forming pan.[19] It is difficult to trace this rumor to its source, although it is not difficult to imagine that it might have come from the brothers themselves, who were masters of deception and jealously secretive about their techniques. Because the Campanis were so successful at guarding their techniques, it is difficult to be certain that they did not discover

[16]Hall and Hall, *Henry Oldenburg*, Vol. 1, p. 327.
[17]Ibid., p. 329.
[18]Ibid.
[19]Huygens, *Oeuvres*, Vol. 5, pp. 107–10.

a way of working the lens directly on the lathe, an issue that is further complicated by a proliferation of similar claims in the later 1660s by writers like D'Orleans, Manzini, Hooke, and others. However, when the contents of Giuseppe Campani's optical workshop were purchased by Pope Benedict XIV in 1747 and examined by an emissary from the French Académie, the report gave no evidence for the claim. The inspector, Fougeroux de Bondaroy, claimed to have seen many carefully worked forming pans in the collection and a lathe for making forms little different from that designed by Maignan (Figure 25).[20] I have found no evidence that Campani's success at grinding lenses derived from anything other than his assiduous attention to craft details, his careful levigation of abrasives, and his refined technique of polishing on paper under carefully controlled conditions.[21] Because of the excellence of his work and his clandestine behavior, many innovative techniques were ascribed to him by other artisans well into the eighteenth century.

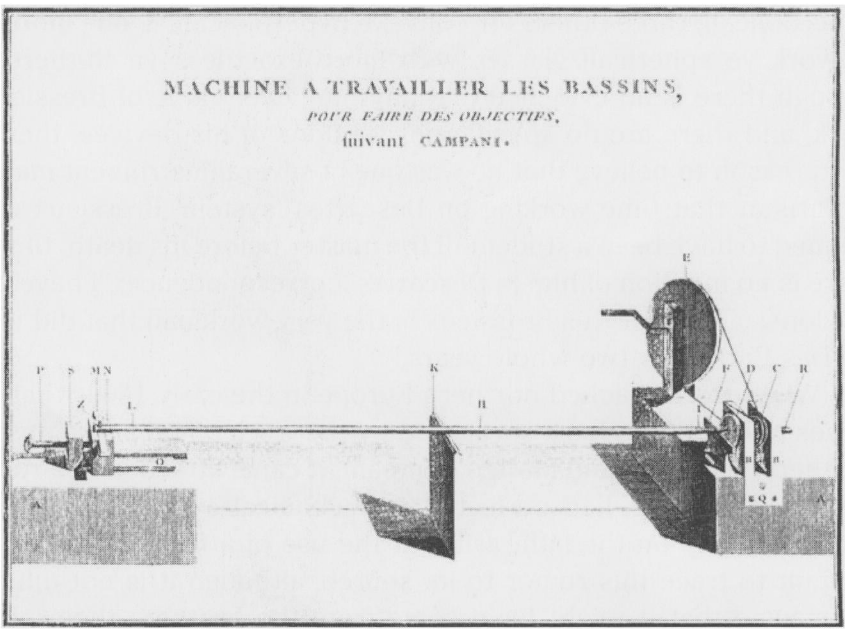

Figure 25 Campani's lathe (de Bondaroy, "Mémoire sur les Objectifs," p. 251)

[20]This machine may be misinterpreted in caption 6 in Bedini's 1966 article "Lens Making for Scientific Instrumentation." The claim there is that Fougeroux believed Campani's lathe to have ground glass directly, while Fougeroux refers to it as a "Machine à travailler les bassins, pour faire des objectifs."

[21]See n. 38 of chapter 1, supra.

HOOKE AND AUZOUT

When word of Campani's putatively "formless" method reached the industrious Robert Hooke in 1664, he set to work to figure out how this might be done. The result was the spherical lens grinding machine illustrated on the first plate of his celebrated 1665 *Micrographia* (Figure 26).[22] In this device the lens Q is shaped by means of the hollow cylinder or ring, K. The machine works on the principle that the arc of the ring will produce a spherical lens of different radius depending

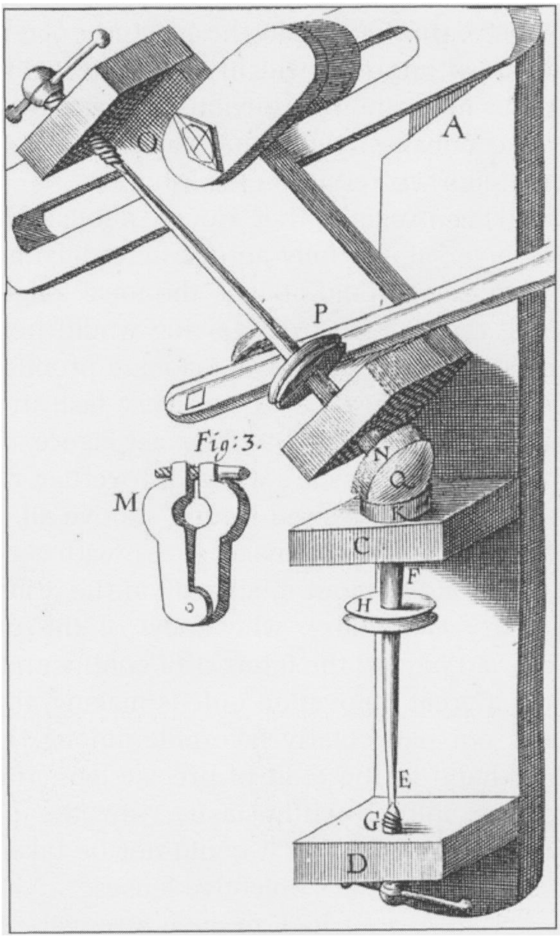

Figure 26 Hooke's lathe (Hooke, *Micrographia*, plate 1)

[22]It is of interest that Hooke turned his microscope on lenses themselves; what he saw helped persuade him that the finest works of art could not approach works of nature in perfection, since "the most smooth and burnished surfaces appear most rough and unpolisht." On this and other aspects of Hooke's work, see Dennis, "Graphic Understanding," particularly pp. 334–35.

on the angle of inclination of the axes of the lens blank and the shaping ring, provided that these axes are perfectly aligned—"the geometrical ground of which being sufficiently plain, though not heeded before, I shall, for brevity's sake, pass over."[23] The ring K contains the abrasive, and, by means of the tailstocks, the work could be advanced as it was ground down by turning.

Hooke did not directly address the question of the hyperbolic lens, but believed that "supposing we had a very ready way of making the object glasses of exactly spherical surfaces, we might, by increasing the length of the glass, magnify the object to any assignable bigness." Hooke believed that increasing the apertures of telescope lenses would account for an improvement in the image field by admitting more light. Perhaps in his limited previous experience with telescope making Hooke had not discovered that astronomers stopped down their lenses in an effort to reduce color fringes.

The lens making "Engine" that Hooke published in 1665 was designed to be universal and fully automatic. Adjusting the angle of the "mandrils" (or axes) would change the focal length of the lens, just as increasing the diameter of the ring would permit a lens of greater aperture to be produced. The machine promised speed and ease and self-regulation because "to the very last stroke the Glass does regulate and rectifie the tool to its exact Figure; and the longer or more the Tool and the Glass are wrought together, the more exact will both of them be of the desired Figure." Above all, the spherical-lens making machine promised to make lenses "with very little trouble in fitting the Engine and without much skill in the grinder."

Although Henry Oldenburg, who knew of the design for the machine in 1664, had piqued the interest of continental virtuosi with letters promising a great innovation in lens making, the response to the machine was not particularly favorable among those who had actually set their hand to the craft of precise lens grinding.[24] When Christiaan Huygens, initially enthusiastic, saw the design for the machine, he wrote his father that it could not be taken seriously as a new method for making exact objective lenses.[25]

In France, Adrian Auzout had an even stronger reaction to the device when he saw the *Micrographia* in early 1665. He submitted a seven-page animadversion on the device to the Royal Society, which was translated by Henry Oldenburg and printed, with a reply from

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[23]Hooke, *Micrographia*, preface.
[24]Hall and Hall, *Henry Oldenburg*, Vol. 2, pp. 282 and 306, letters to Huygens and Hevelius.
[25]Huygens, *Oeuvres*, Vol. 5, p. 240.

Hooke, in *Philosophical Transactions* number four, of June 1665. Auzout was a respected critic on questions of lens making, being one of the founding members of the Société de Lunetterie in Paris, an association of savants and craftsmen who met regularly to discuss and exchange techniques for lens grinding and design. It was in the company of this society that Huygens and Petit and other seventeenth-century luminaries met to discuss the fine points of emery, tripoli powder, and lathe design.[26] Auzout even traveled to Italy in order to compare his thirty-five-foot telescope objective to those of Campani and Divini, and believed that his own work equaled that of Divini, though remained inferior to that of Campani.[27]

Auzout's familiarity with the intricacies of the craft practice of lens grinding left him impatient with the naive mechanization of Hooke's device. "The preciseness and delicateness is greater than can easily be imagined," he wrote in an open letter to Hooke, "wherefore he could never, having some experience of this preciseness, conceive, that a *turn-lathe,* wherein must be two different and in some manner contrary motions, can move with that exactness and steadiness that is required, especially for any considerable length of time." Auzout expressed surprise that a work of "mere theory" could have found the sanction of the Royal Society. What, he wondered, had become of their motto, "Nullius in verba?" Explicitly introducing the distinction between theory and practice, that hobgoblin of the mechanical philosophy, Auzout also directly addressed the difference between the idea of a machine and an actual physical device:

> Though it be true in the Theory, that a Circle whose Plain [*sic*] is inclined to the Axis of the Sphere by an Angle, whereof half the Diameter is the Sine, and which touches the Sphere in its Pole, will touch in all its parts a Spherical Surface, that shall turn upon that Axe. But it is true also that that must be but a Mathematical Circle, and without Breadth, and which precisely touches the body in the middle: Whereas in the practice a Circle capable to keep Sand and Putty, must be of some breadth.[28]

Moreover, Auzout argued that it was impossible to imagine a mechanical system that could maintain the alignment of the two spinning axes, particularly as the work was ground down. Though he proceeded to offer several practical suggestions as to how the design might be improved (such as the addition of screws to maintain the

[26]McKeon, "Adrian Auzout," chap. 3, passim.
[27]Van Helden, "Telescope in the Seventeenth Century," p. 48, n. 51.
[28]*Philosophical Transactions* 1, no. 4 (1665): 58 (italics omitted).

alignment of the spinning shafts and the placing of the glass under the ring rather than over it so as to ease the strain on the pitch-putty used for binding the glass onto the shaft), Auzout harbored grave doubts about the potential usefulness of Hooke's machine. The problem was the gap between mechanized mathematical diagrams and machines of metal and wood, the incommensurability between the mechanisms of the mechanical philosophy and machines in the world.

Hooke's response, also published in the *Philosophical Transactions,* was respectful but largely dismissive of the practical concerns raised by Auzout in his critique. Instead of recognizing that the burden of proof lay on him as the inventor, clever Hooke tried to turn the tables on Auzout's accusation that the machine was "mere theory." What were Auzout's objections, he asked, but more "theory"? Why, Hooke asked, should he be attacked for presenting theory without experiments, if Auzout himself had not experimented with the machine? Several times during the defense of his machine, Hooke wrote of the mechanism and its components as if they did not belong to the physical world. There should be no difficulty making lenses of great size provided that the "Mandrils [Axes] and tools be made sufficiently strong, so that they cannot bend." "As to the wriggling and playing of the Mandril," he wrote, "I do not understand it."

Most telling of Hooke's attitude toward the machine is the introduction to his response, in which he betrays his faith in the regularity, rigidity, and accuracy of mechanism:

> As to the exceeding exactness of the figure of long object-glasses, 'tis not doubted, but that it is a matter difficult enough to obtain by any way: but yet, I think much easier by *Engine* than by *Hand*; . . . And for making spherical glasses by an *Engine*, I am apt to think, there can hardly be any way more plain, and more exact, than that which I have described; wherein there is no other motion, than that of two such mandrils, which may be made of sufficient strength, length and exactness, to perform abundantly much more, than I believe possible to be done otherwise than by chance, by a man's hands or strength unassisted by an Engine, the motion and strength being much more certain and regular.[29]

Auzout read Hooke's reply and penned another letter to Henry Oldenburg, pointing out the fallacious logic Hooke had used to defend

[29]Ibid., p. 66.

his project. Auzout noted that the burden of proof was upon the inventor not upon the critic, and pointed out the essential criterion for distinguishing a machine in the mind from a machine in the world—*efficacity:*

> I think that when doubts are raised about the working of a machine it is not enough to respond to the reasons given for those doubts; since the question is whether it works or not, the only thing to do to silence those who raise doubts is to show them how it can be made to work, and any other reply is in danger of being useless.[30]

This letter was not printed in the *Philosophical Transactions,* and although there is evidence that Hooke was quite serious about trying to build the device and prove his detractors wrong, his hyperactive undertakings did not allow him a moment to work on the machine.[31] The interruption of the normal functions of the Royal Society, as a result of the plague in the summer of 1665, set back the project still further as Hooke and others fled to the countryside.[32] The additional demands placed on Hooke as an architect as a result of the great fire in 1666 delayed the project again, and in late 1667 Hooke was still interested in lens making but was grinding objectives by his own hand in forms (which may suffice as an indication of the validity of Auzout's criticisms).[33]

Part of the reason that Hooke's device faded from interest in the late 1660s may have been the design of an innovative hyperbolic lens making machine by one of Hooke's colleagues, Christopher Wren. European virtuosi had not lost interest in the promise of the hyperbolic lens in the wake of the failed attempts that followed the initial fascination introduced by *La Dioptrique*. Throughout the period most savants remained convinced that the hope for great improvements in telescopes rested on the hyperbolic project. In the words of Fermat, writing more than ten years after Descartes' death: "We will have to wait on the marvels that Monsieur Descartes has rightly caused us to hope for in the elliptical and hyperbolic lenses, until we can find workers sufficiently skilled to make and finish them."[34]

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[30]Hall and Hall, *Henry Oldenburg*, Vol. 2, p. 419.

[31]Ibid., Vol. 3, p. 15. This is a claim Hooke resorted to more than once when called upon to give substance to a tantalizing promise.

[32]Ibid., Vol. 2, pp. 442 and 452, letters to Auzout and Hevelius.

[33]Ibid., Vol. 3, p. 348.

[34]Huygens, *Oeuvres*, Vol. 4, p. 79.

WREN AND THE BROTHERS HUYGENS

In 1669, Christopher Wren presented an "engine designed for grinding hyperbolic lenses" to the Royal Society.[35] The machine was based on Wren's discovery that there are straight lines continuous with the surface of a three-dimensional hyperboloid of one sheet (Figure 27).[36] He then realized that such a hyperboloid could therefore be generated by a straight line—for instance by inclining a straight blade to the edge of a spinning cylinder.[37] The resulting hyperbolic form could then be used to grind a lens by bringing the spinning lens blank up against the spinning form (with the two axes of rotation set to intersect at a right angle). Knowing that the hyperboloid form would be ground away by contact with the glass blank, Wren worked out a way to make the device "self-regulating" by having two cylinders, at an angle to

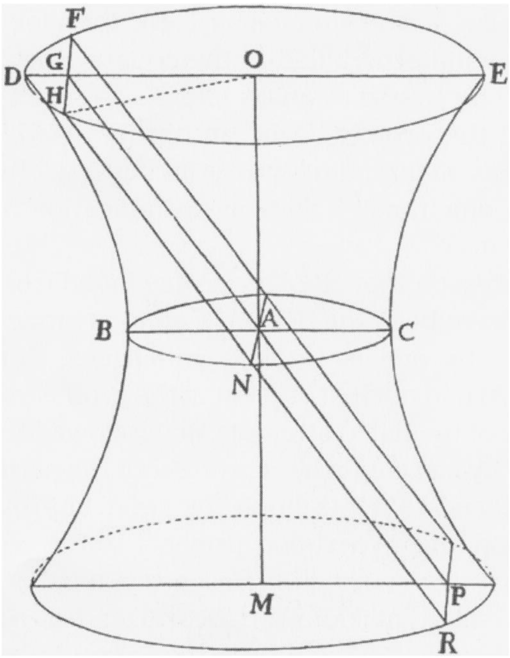

Figure 27 Wren's diagram (*Philosophical Transactions of the Royal Society,* Vol. IV, no. 48, plate)

[35]*Philosophical Transactions* 4, no. 53 (1669): 1059–60; and also 3, no. 48 (1669): 961–62. Note the earlier announcement of the invention of such a device, by Smethwick (a fellow of the Royal Society), in *Philosophical Transactions* 3, no. 33 (1668): 631–32. No description is given.

[36]The principles for the evolution of a hyperbola in this way can be found in Wren's contribution to *Philosophical Transactions* 4, no. 48 (1669): 961–62 (and plate).

[37]It would be interesting to know if this observation proceeded from lathe work, where the phenomenon of this evolution would have been easy to observe.

one another, cut each other into hyperboloids while the glass blank ground against them perpendicular to their axes.[38] This is the arrangement that appears illustrated in the *Philosophical Transactions* of November 1669 (Figure 28).

Once again Oldenburg had forewarned his continental correspondents to expect a great innovation shortly, going so far as to explain to Huygens the principle of the device. Again, the reaction to the publication of the device was mixed, and Huygens himself was not optimistic. Huygens' initial concern—that an actual blade would need to be infinitely fine to cut a cylinder to an accurate hyperboloid—was addressed by the clever addition of the second cylinder to the published design.[39] But Huygens' doubts persisted even after he saw the improved design. He pointed out that the lens blank made contact with the form along a single line, which he believed would make the lens very difficult to polish.[40] Others were more optimistic.

René François de Sluse, a learned cleric whose mathematical works on the cycloid gained him the praise of Pascal and others, was particularly excited by the promise of the device, and he set out to prove that different configurations of the components of the device would permit any hyperbolic lens to be ground.[41] Thus the system soon promised to be universal as well as self-regulating. Sluse, first

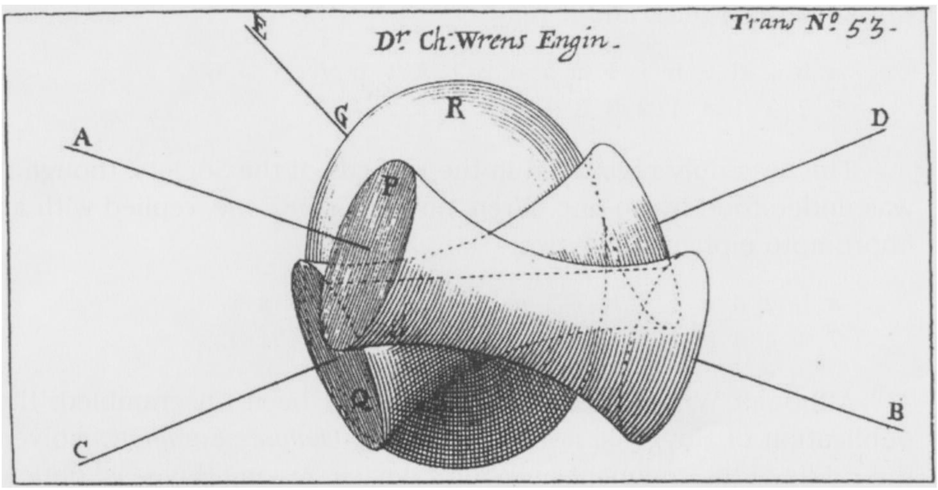

Figure 28 Wren's machine (*Philosophical Transactions of the Royal Society,* Vol. IV, no. 53, plate)

[38]Hall and Hall, *Henry Oldenburg,* Vol. 6, p. 306.
[39]Ibid., p. 163.
[40]Ibid., p. 425.
[41]Ibid., p. 184.

and foremost a mathematician, was less ready than an experienced lens maker like Huygens to perceive the ways that "practice may defraud theory."[42]

Although there is some evidence that Wren actually sought out an instrument maker to realize a version of his machine, the diagram presented in the *Philosophical Transactions* is not a machine at all but a representation of the geometry that underlies the proposal: it has no moving parts, structure, or mechanism, but represents the hypothetical machine in its abstract formulation. "To describe this thing," he wrote in his description of the diagram, "by painstaking diagram and long explanation would be to my craftsman and myself more troublesome than for some clever Dædalus to invent the thing." Thus, in order to simplify the construction of the machine in the reader's mind, he omitted, as he put it, "wheels, cogs, straps, weights, spirals and all the remaining things necessary for swift motion and a steady machine." That is to say, in the design of the machine he omitted the actual machine. Wren's device, like the other mechanical systems for making lenses, was never realized, not because the machine would not work in the mind, but because it would not work when brought into the realm of the wooden wheel and the brass cog.

Of all the replies to the publication of Wren's machine, the most curious was that sent to the Royal Society in late January 1669 by Christiaan Huygens, and it read:

a	b	c	d	e	h	i	l	m	n	o	p	r	s	t	u	y
5	2	2	1	4	1	2	3	3	1	3	2	2	3	2	4	1[43]

This was duly registered in the records of the Society, though it was understood by no one. Wren, not to be outdone, replied with an impromptu cipher of his own:

a	b	c	d	e	f	g	h	i	l	m	n	o	p	r	s	t	u	x	y
7	4	4	4	12	1	3	6	10	7	1	7	9	2	6	2	7	4	1	1

Although Wren's "response" has never been unscrambled, the publication of Huygens' notebooks in the *Oeuvres Complètes* solved the riddle of his comment on Wren's device. Among Huygens' optical works of the late 1660s is found a paper entitled "De Aberratione Radiorum A Foco," at the end of which the same anagram is written,

[42]Oldenburg to Sluse on the foreseen difficulties with Wren's machine. Ibid., p. 448.

[43]Ibid., p. 362. On anagrams as a mode of establishing priority (and a form of intellectual property), see Ravetz, *Scientific Knowledge*, pp. 248–49.

under the Latin words "Lens e duobus composita hyperbolicam aemulatur," that is, a lens composed out of two rivals the hyperbola.

The meaning of this cryptic statement can be derived from a closer examination of the content of "De Aberratione." The work in these pages was dedicated to the design of a composite objective lens made from a plano-convex and a biconcave lens, both of spherical shape. Huygens demonstrated that by varying the radii of the spherical sections of the two elements, this configuration of lenses could correct for spherical aberration (Figure 29). Having completed this proof early in 1669, Huygens recognized the implications for the project to grind hyperbolic lenses but probably desired to build a model of his new system before making public his discovery, and thus he lodged his

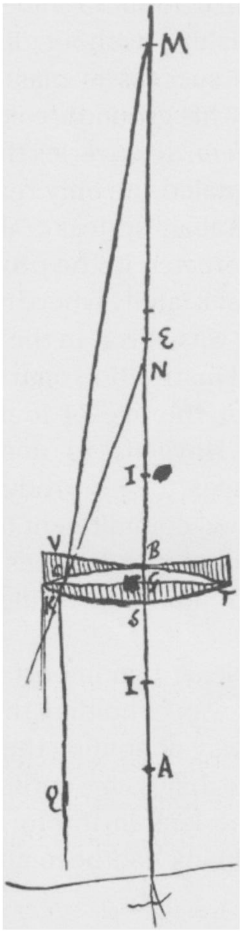

Figure 29 Huygens' double lens (Huygens, *Oeuvres Complètes*, Vol. XIII, pt. 1, p. 411)

cipher at the Royal Society by way of a proof of his primacy as inventor of the composite objective.

Huygens had largely despaired of the utility and practicality of hyperbolic lenses almost twenty years before his discovery of the composite objective, when, in 1652, he worked out a description of an "aplanatic" spherical lens that he believed would not introduce spherical aberration to rays coming from a predetermined point.[44] According to the editors of the collected works, it was the promise of these lenses that compelled Huygens to set himself to learn the craft of lens making, for which he corresponded with Gutschoven, Descartes' former student, and almost certainly had some contact with artisans known to his father.[45] Apart from brief experimentation with making hyperbolic lenses in 1654, Huygens concentrated on mastering the craft of grinding and polishing spherical lenses, following for the most part the instructions he received from Gutschoven on preparing forms and polishing without distorting the shape of the lens. The evidence of his success in mastering the craft aspects of lens making is provided by his groundbreaking observations of Saturn in his 1659 *Systema Saturnium*, discoveries that heralded the excellence of his instruments and signaled the only real challenge of the century to the supremacy of the Italian optical craftsmen.

Huygens was also interested in the prospect of mechanizing lens making, having grown up in a family where mechanical skill was highly prized. Christiaan's father was adroit in the use of the lathe and Christiaan himself had received instruction on it and had even constructed a turn-lathe of his own at the age of fourteen.[46] These precocious abilities surely inspired Huygens to consider the application of lathelike mechanical devices to the production of lenses, a project that paralleled his continued commitment to craft practice. This commitment to both craft techniques for lens making and the promise of mechanization resulted in an interesting tension in Huygens' lens making work.

Huygens designed at least two important new tools to aid in the handcraft of lenses: a new way of holding the lens-blank while shaping it on the form; and a new way of holding the lens and pressing it down to be polished. In the late 1650s, he outlined the improved "bâton" technique for handling the lens in the forming pan (Figures 30 and 31).[47] Previously the lens-blank had been affixed by means of pitch or

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[44]Huygens, *Oeuvres*, Vol. 13, p. xlvi.

[45]Ibid, Vol. 17, p. 249.

[46]Ibid., p. 248.

[47]Though Beeckman had discussed such a tool in the 1620s. See De Waard's "Notes sur le Rodage," p. vii. These references, contrasting the "vaste dop," or constrained mollette, with the "losse dop," or free hand, constitute the earliest reference to this tension.

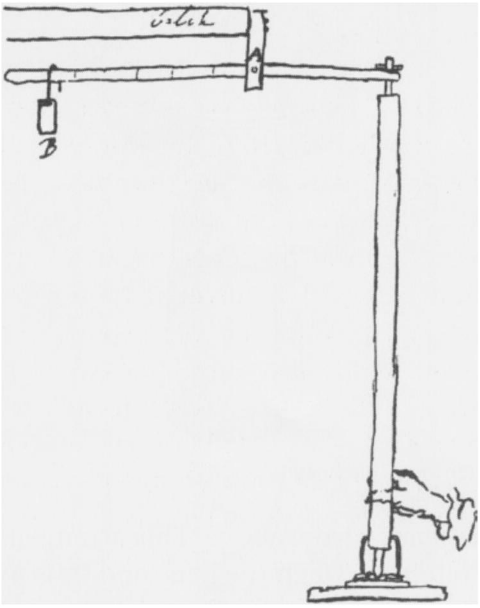

Figure 30 Huygens' baton technique (Huygens, *Oeuvres Complètes*, Vol. XVII, p. 299)

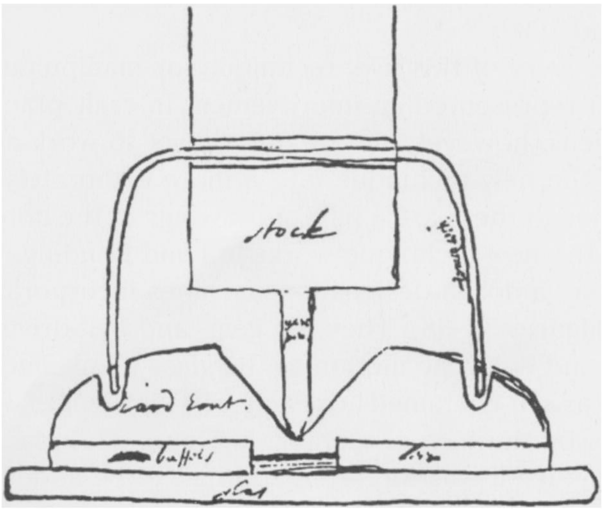

Figure 31 Huygens' baton technique, detail (Huygens, *Oeuvres Complètes*, Vol. XVII, p. 300)

rosin to a short wooden or stone handle called a mollette (Figure 32). This short handle and the wide distribution of force over the surface of the glass could lead to a rocking of the blank as it was guided over the form, resulting in distortions of shape. Huygens' improvement made use of an iron pin which acted as a bearing in the center of a piece of wood sitting over the glass. This pin was affixed to a wooden

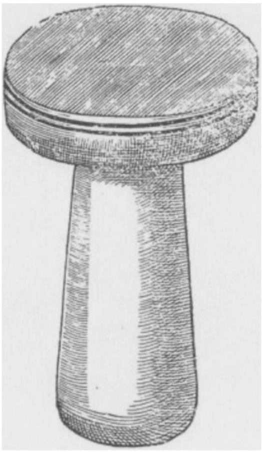

Figure 32 Mollette (Sirtori, *Telescopium,* p. 47)

shaft that was suspended from above. This arrangement did not necessitate the use of pitch to attach the lens, and thus avoided fouling the abrasive with fragments of rosin. The technique must have worked well, because Huygens referred to using it into the early 1660s and even dedicated to it several pages of his extensive *De Vitris Figurandis*, published posthumously (in 1703) but representing work done during the 1670s and 1680s.[48]

The discovery of this new technique for manipulating the glass blank, which represented an improvement in craft practice, did not satisfy Huygens, however, and he quickly set to work attempting to incorporate the new technique into a more elaborately mechanical system. Although there are a pair of drawings in the notebooks illustrating how the new technique works in hand grinding, there are no fewer than half a dozen designs for machines incorporating the new technique (Figures 33–38). They are gear- and belt-driven, imparting both rotary and epicyclic motion to the glass blank, and they are all represented as self-contained boxes out of which lenses would emerge more or less by the turn of a crank. In Figure 37, in fact, it appears that the crank itself was forgotten and had to be added as an afterthought—a *pentimento* that speaks volumes concerning the preoccupation with extensive mechanization of the process. Huygens, though always committed to handcraft and aware of the complexity of lens making, was never entirely seduced by his own speculations, and he never confused the promise of mechanical ideas with actual grit and glass: beside the best-wrought design of his lens grinding machines

[48]Huygens, *Christiani Hugenii.*

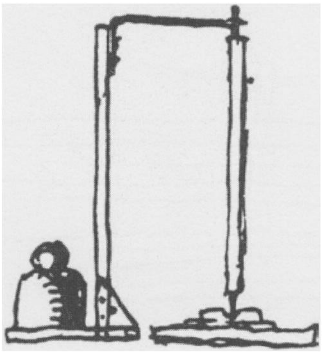

Figure 33 Huygens' continued work with baton (Huygens, *Oeuvres Complètes,* Vol. XVII, p. 301)

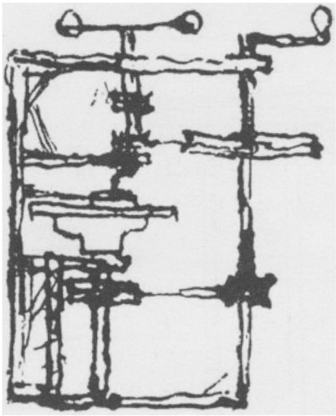

Figure 34 Huygens' machine 1 (Huygens, *Oeuvres Complètes,* Vol. XVII, p. 301)

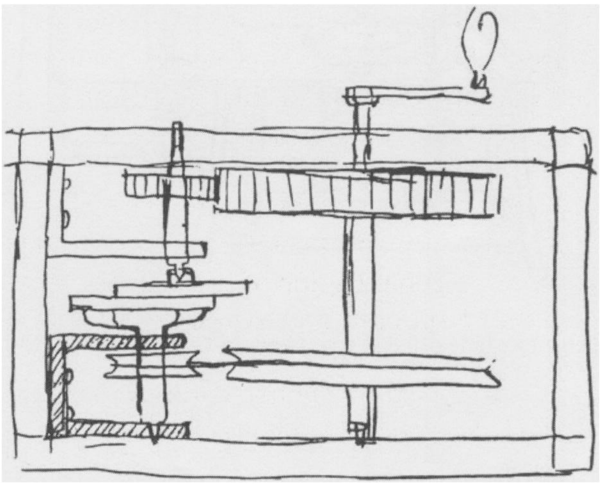

Figure 35 Huygens' machine 2 (Huygens, *Oeuvres Complètes,* Vol. XVII, p. 302)

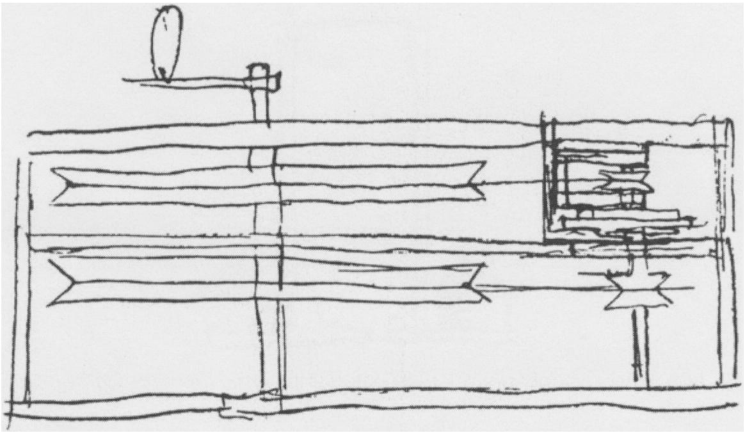

Figure 36 Huygens' machine 3 (Huygens, *Oeuvres Complètes*, Vol. XVII, p. 302)

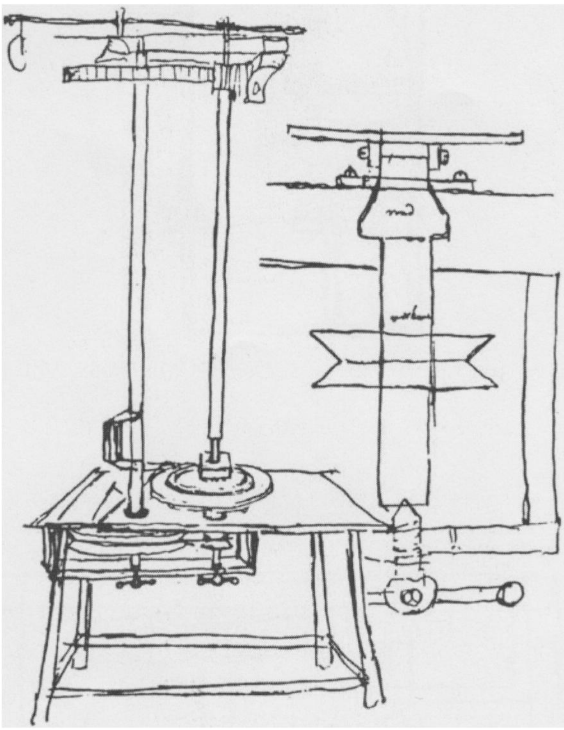

Figure 37 Huygens' machine 4 (Huygens, *Oeuvres Complètes*, Vol. XVII, p. 303)

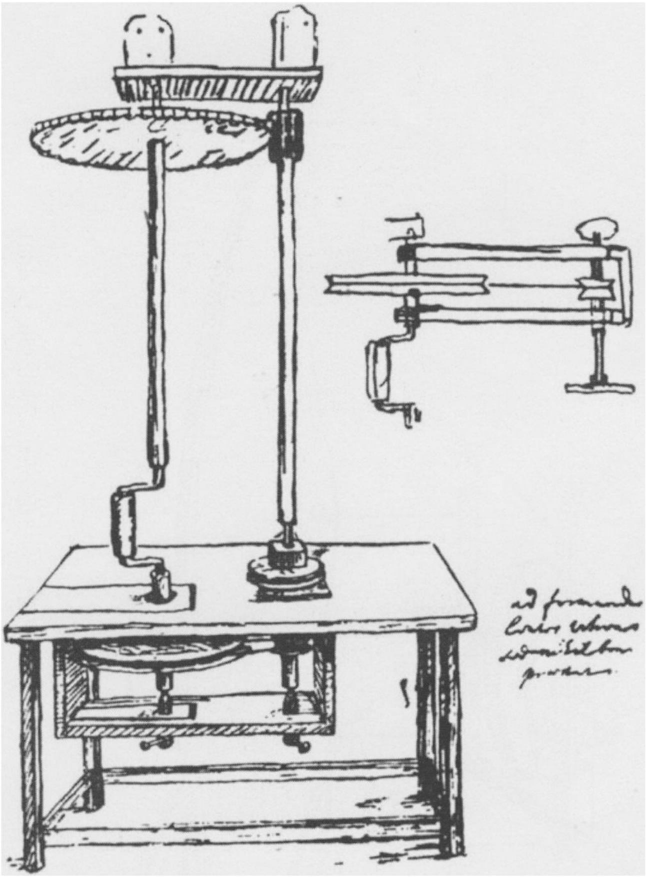

Figure 38 Huygens' machine 5 (Huygens, *Oeuvres Complètes,* Vol. XVII, p. 304)

(Figure 38) is written, "ad formandas lentes vitreas sed nihil boni praestat."[49]

Christiaan, together with his brother, also designed a grinding and polishing technique for larger lenses, which was used with some success in the 1680s. This device consisted of a forming-table and a treadle bar by means of which the larger lens could be guided about the form under an even downward pressure (Figures 39 and 40). Once again, however, the promise of an automatic, mechanized system provided a powerful attraction, and the design of the same device presented in *De Vitris Figurandis* is represented as a machine capable of producing lenses with the turn of a crank (Figure 40). Huygens' work

[49]"For the making of glass lenses, but nothing good comes of it."

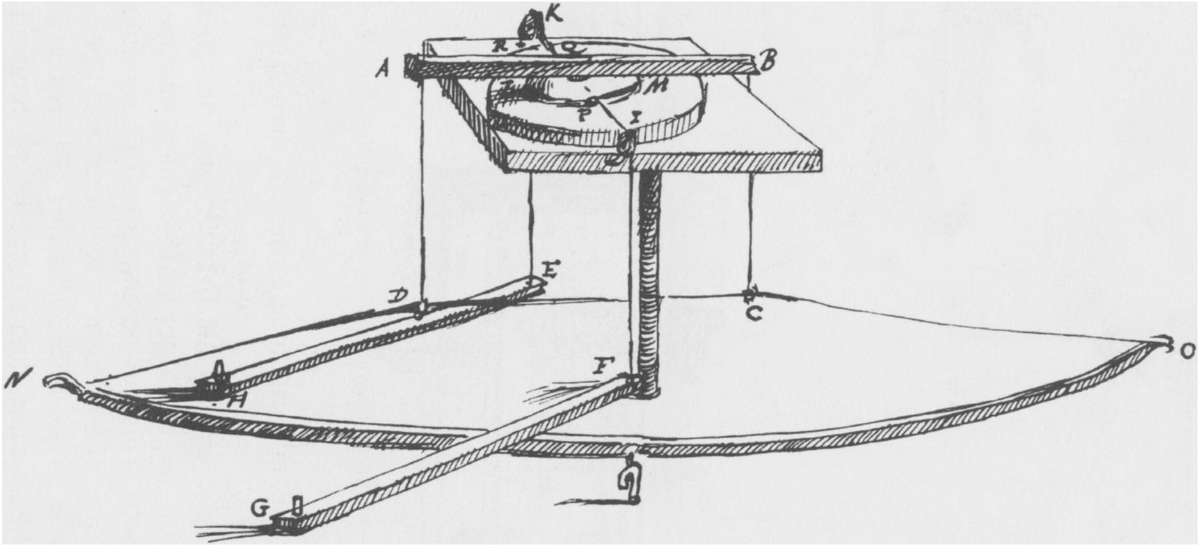

Figure 39 Huygens' machine 6 (Huygens, *Oeuvres Complètes*, Vol. VIII, p. 432)

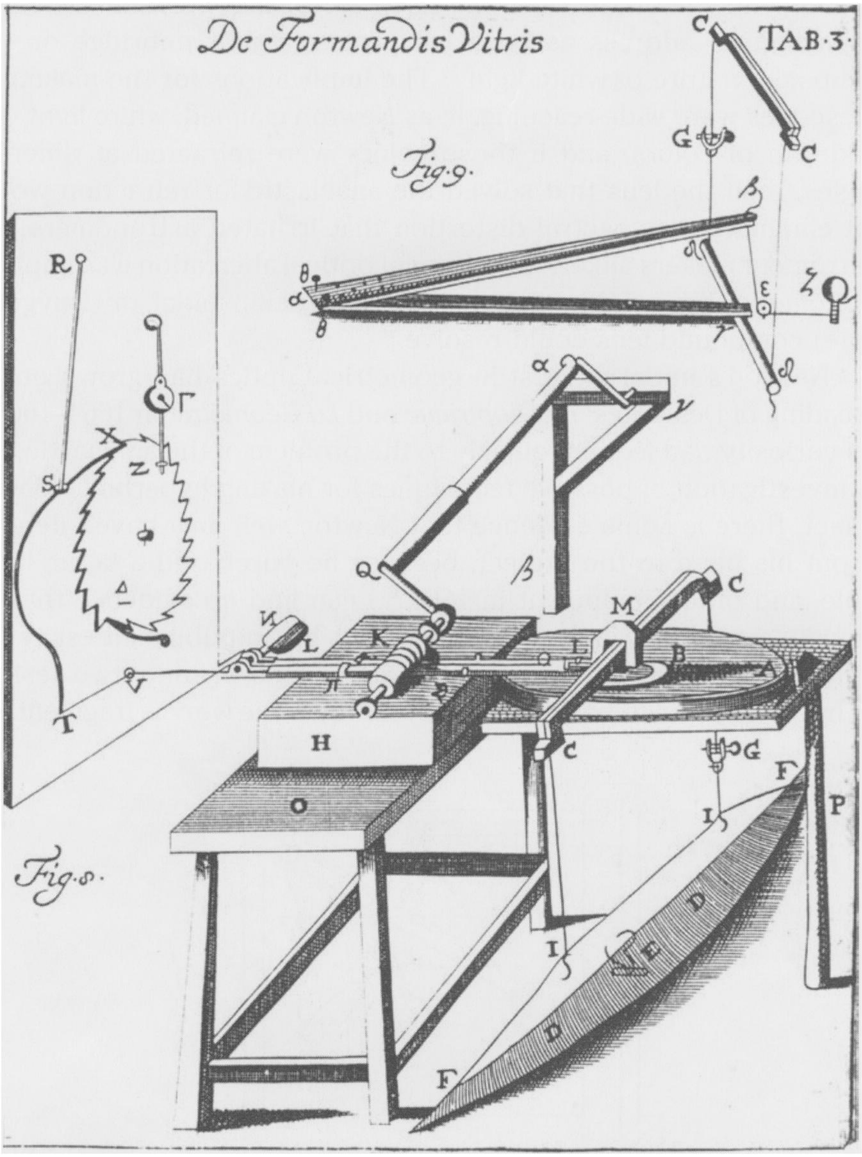

Figure 40 Huygens' machine 7 (Huygens, *Christiani Hugenii*, p. 290)

makes abundantly evident the pervasive tension between the amelioration of handcraft techniques and the replacement of the hand by the machine. Though he was consistently skeptical of the actual feasibility of the mechanized systems proposed by Hooke, Wren, and others, Huygens himself could not resist the promise of the mechanical maker.

NEWTON AND THE END OF THE HYPERBOLIC QUEST

Both Wren's machine to make hyperbolics and Huygens' idea of the composite objective (as an emulation of the hyperbola) were destined

to meet the same fate when, in early 1670, Isaac Newton delivered his inaugural address as Lucasian professor at Cambridge on the composite nature of white light.[50] The implications for the making of telescopes were wide-reaching. If, as Newton claimed, white light was made up of colors, and if those colors were refracted at different angles, then the lens that solved the anaclastic for refraction would not eliminate the spectral distortion that irritated astronomers and instrument makers alike. A new form of optical aberration was implied, a *chromatic* aberration, which no hyperbolic, ellipsoidal, or (Huygens-style) compound lens could resolve.[51]

Newton's initial interest in geometrical optics had grown out of a reading of Descartes' *La Dioptrique* and *La Géométrie* in 1664–1665.[52] His curiosity had led him quickly to the problem of the anaclastic and an investigation of possible techniques for making hyperbolic lenses. In fact, there is some evidence that Newton well may have intended to put his hand to the project, because he purchased a lathe, lathe table, and other equipment in 1667.[53] I can find no evidence that he actually succeeded in making lenses, but his unpublished essay "Of Refractions," written in the winter of 1665 or 1666, includes two designs for hyperbolic machines (Figures 41 and 42).[54] The work is fragmentary,

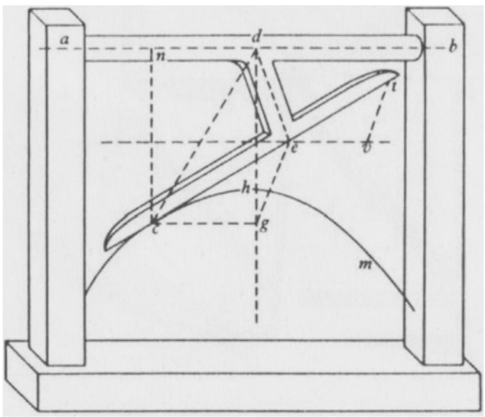

Figure 41 Newton's hyperbolic technique, redrawn (Whiteside, ed., *Mathematical Papers*, Vol. I, p. 561)

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[50]Shapiro, *Optical Papers*, Vol. 1, p. 13.

[51]In the eighteenth century a different sort of compound lens system would be used to eliminate chromatic aberration.

[52]Shapiro, *Optical Papers*, Vol. 1, p. 13.

[53]Ibid., p. 11.

[54]The relevant portions from "Of Refractions" are reproduced in Whiteside, *Mathematical Papers*, Vol. 1, pp. 559–76 (from which these re-drawings have been taken). For a facsimile of the manuscript designs for the machines, see Westfall, *Never at Rest*, p. 162.

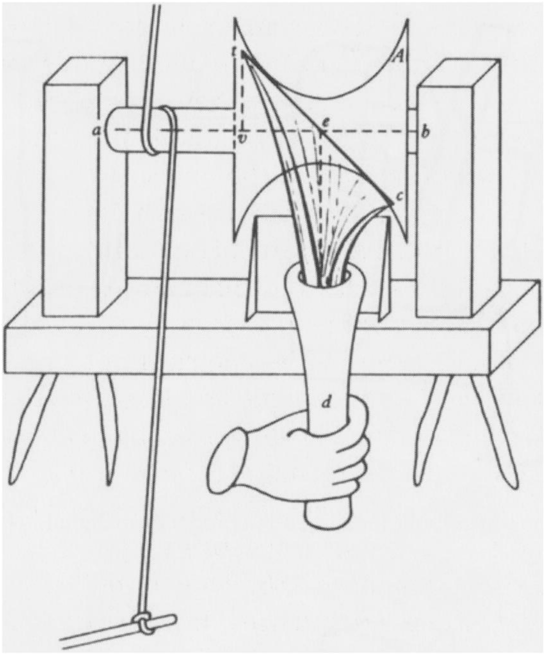

Figure 42 Newton's hyperbolic technique 2, redrawn (Whiteside, ed., *Mathematical Papers*, Vol. I, p. 562)

and correspondingly difficult to interpret, but in the first device it appears that the bar labeled cet is not coplanar with the axis ab, making cet trace out a hyperboloid when rotated around ab. Sketches of what appears to be this same device, showing the glass blank in position to be ground, can also be found in another Newton manuscript (Figures 43 and 44).[55] This design and that of the other device (see Figure 42) seem to give priority to Newton in the discovery of the generation of the hyperboloid by means of a straight edge inclined to the axis of a cylinder, the technique (independently?) discovered by Wren in 1669 (see Figures 27 and 28, pp. 92, 93).

With the publication of his theory of colors in the *Philosophical Transactions* of 1671–1672 and the demonstration of his "experimentum crucis" for the composite nature of white light, Newton began to find supporters for his theory both in England and on the Continent. Inquiries concerning Wren's machine from the likes of Leibniz and

[55]For a discussion of these designs, see Bedini, "Lens Making for Scientific Instrumentation," p. 692. Unfortunately, Bedini's citation (to Newton, *Opticks*, p. 83) is erroneous, and I have not been able to trace the provenance of these sketches; evidence elsewhere in Bedini's article suggests they appear in manuscripts held at Cambridge.

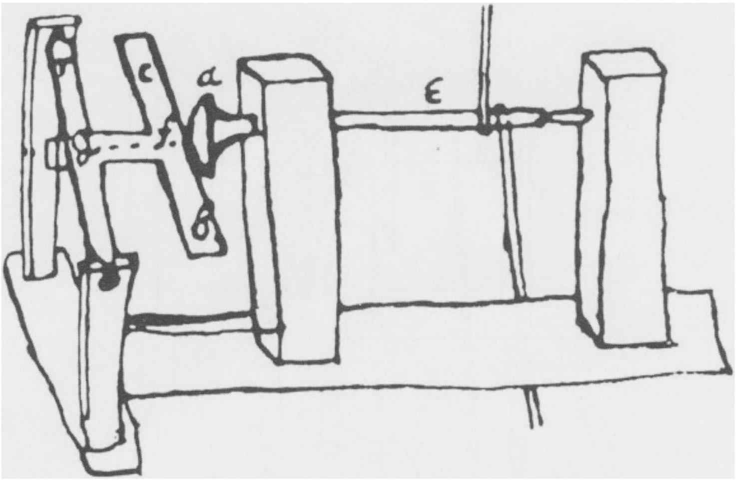

Figure 43 Newton's hyperbolic technique 3 (reproduced in Bedini, "Lens Making," p. 692)

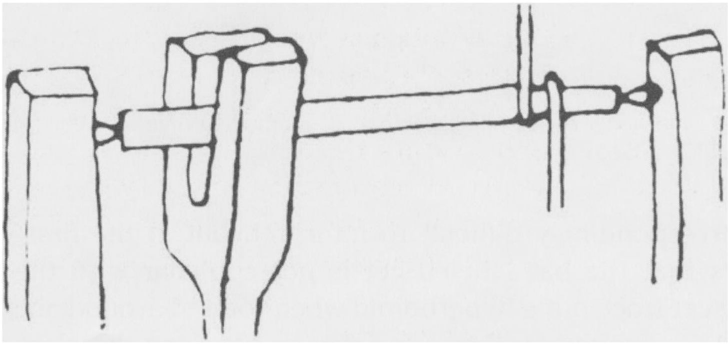

Figure 44 Newton's hyperbolic technique 3, detail? (reproduced in Bedini, "Lens Making," p. 692)

Hevelius ceased arriving at the Royal Society, and in Holland, Christiaan Huygens scribbled a telling note in the margin of his sketches of the compound objective (Figure 45):

> P.S. Hoc inutile est inventum propter Aberrationem Newtonianam. . . . [56]

By late 1671 the new project among virtuosi and instrument makers was shaping specula for use in the new Newtonian reflecting telescopes, and the hyperbolic lens (together with Huygens' compound objective) was forgotten.

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[56]Huygens, *Oeuvres*, Vol. 13, p. 409, n. 2.

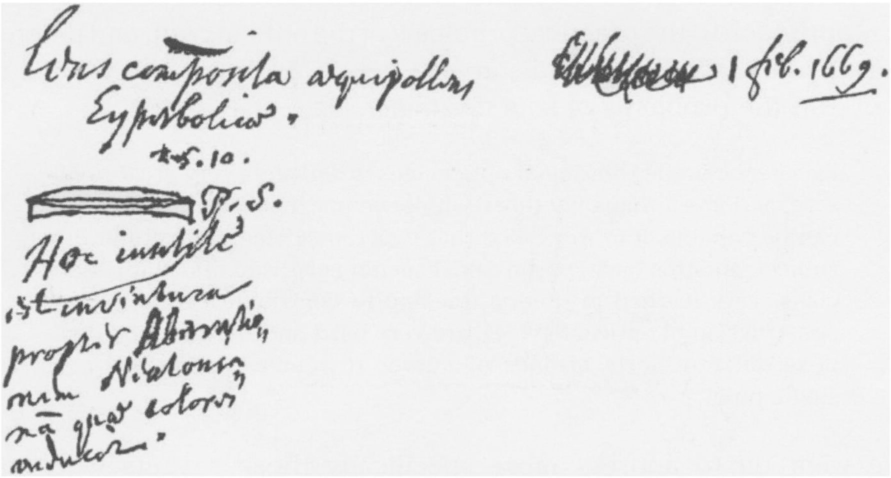

Figure 45 Huygens' annotation (Huygens, *Oeuvres Complètes,* Vol. XIII, pt. 1, p. 304)

Mechanical lens making and mirror making, however, were not forgotten, and when it was realized that the metals used for making specula were too soft to maintain adequately the polish necessary to make large reflecting telescopes feasible, the precise spherical lens again bore all hope for better astronomical instruments. In the eyes of some craftsmen and savants the failure of rational lens design implicit in the discovery of chromatic aberration represented a broader failure of "theoretical" incursions on the space of the artisan, and although the promise of mechanical making was not forgotten, the feasibility of complete systems for mechanical fabrication came under a new and systematic critique.

D'ORLEANS AND MECHANICAL LENS MAKING AT THE END OF THE CENTURY

Cherubin D'Orleans, the author of the most exhaustive treatise on lens making in the seventeenth century, provides a salient example of this potent critique of misapplied theory. While recognizing the shortcomings of handcraft, D'Orleans, a Capuchin friar, also recognized the weaknesses of mechanical systems. Ultimately, he combined his encyclopedic knowledge of the craft of optical glasswork with a commitment to mechanical tools, producing a new approach to lens making in his text *La Dioptrique Oculaire*, published in 1671.[57]

[57] I have found essentially no detailed recent discussions of D'Orleans. A number of his surviving instruments are mentioned in Daumas, *Les Instruments Scientifiques*, pp. 47, 49–54; and Bedini, "The Tube of Long Vision," pp. 198–201 (includes two plates). *La Dioptrique Oculaire* receives some attention in Malet, "Kepler and the Telescope," pp. 127–31.

D'Orleans clearly recognized the failure of the excessively theoretical approach to the practical problems of the optical craft, and pointed out the importance of hands-on experience for those who wished to work on the problems of lens making:

> Excellence in the working of optical lenses demands very great precision, and given this, only those who have put their hand to the work can be capable. It is witnessed that experience leads to truth in this subject, and this having been said, I am not surprised that Mathematicians, very learned in theory, thinking to contribute to the perfect construction of optical devices, are very hard put to invent and compose different sorts of lines or curves to reunite visual rays at a single point.[58]

He went on to address more specifically those savants who had become preoccupied by the anaclastic problem and the promise of the hyperbolic lens:

> In their thoughts, these hope to rectify the fault of the circle, which does not concentrate at a single point all homogeneous rays . . . . I dare to say that if they had accompanied their Theory with some Practice, they would have saved themselves time and work on the research of these shapes even just by this consideration: that despite the simplicity, regularity, and ease of description of the circle in comparison with all other curves, it is nonetheless extremely difficult to form glass exactly to this shape with sufficient precision and size to produce worthy effects.[59]

D'Orleans declared, in effect, a pox on both houses: that of the speculative mechanizer and the vulgar artisan. The shortcomings of handcraft and "simple machines" were what compelled those who sought to build complex mechanized lens making systems, but D'Orleans had no illusions about the real potential of mechanical systems, and he rejected the overmechanization characteristic of speculative mechanics. Instead of attempting to replace the artisan by the machine, D'Orleans sought to incorporate the mechanical tool and the skilled artisan into a single lens making system, not simply guided by the rigidities of mechanics (or mathematics) but making use of the rectifying hand of the skilled craftsman as well:

> Having the intention here of making use of several instruments or machines to direct the hand of the Artisan in the working of optical

[58]D'Orleans, *La Dioptrique Oculaire*, p. 405.
[59]Ibid., p. 406.

> lenses, I have done it in such a way that these devices be the most simple, and least composite, that the needed effects would permit. I exclude machines of compound motion whenever the artisan can by the application of his hand supply one of the motions, because, being guided by his reason, it is less subject to error.[60]

Only the hand of the artisan could be called truly "self"-regulating, and thus the application of the hand, guided by the *lumière naturelle* of the wise craftsman, provided the machine with a mind: "Being endowed with sense, the hand makes known, in its way, if it is applied exactly, being free in its actions and not compelled or constrained as an inanimate machine would be."[61] For D'Orleans, the proper artisan would be, in a literal sense, the soul of a new machine.

Rejecting the tradition of overmechanization and the quest to replace the artisan by a mechanical system did not mean an uncritical acceptance of the tradition of optical handcraft. D'Orleans wrote astutely of the common failings of the lens makers and critiqued their methods in order to demonstrate his familiarity with the craft and to introduce his innovative techniques. His chapter on the perfecting of forms opened sternly, "It is the common manner of the vulgar artisans . . . ," and he went on to reject their technique as "very defective and sloppy."[62] Eventually, every technique of the common artisan came under attack, from the construction of the mollette to the shaping of forms and the preparation of abrasives. D'Orleans' assault both systematically rejected the methods used by ordinary optical craftsman, and extended criticism to his very person and moral character: "There is the proper manner of preparing a form . . . very different from that of the vulgar artisans, who are as filthy and untidy in their work as they are for the most part coarse and ignorant of their art."[63]

At the opening of the section on lens grinding in *La Dioptrique Oculaire,* D'Orleans asked his reader to avoid assiduously the contamination of the techniques of the common spectacle makers, men "equally ignorant and presumptuous." It is thus clear that despite his willingness to reject the lure of mechanical systems, D'Orleans harbored no illusions about the expertise of common shop practice and had little respect for the common craftsman. In an interesting way, then, D'Orleans stood between the communities of scholars and craftsmen, defining a middle ground between those savants preoccupied by the mechanization of lens making systems and those less

[60]Ibid., p. 380.
[61]Ibid., p. 381.
[62]Ibid., p. 345.
[63]Ibid., p. 363.

skilled opticians-turned-instrument-makers. He addressed a new audience, a new kind of artisan, one who was "intelligent and diligent," as well as "curious, careful, and industrious."[64] This ideal figure, to whom this text belonged, was referred to fraternally throughout the work as "nôtre Artiste," and D'Orleans claimed this new artisan's intelligence and "adroitness" would assure that, after learning a few principles, he would "conduct himself in the work" by means of his own reason.[65]

This new artisan, grounded in theory and able in practice, could not, however, make lenses alone. His lenses would emerge out of the careful and judicious application of D'Orleans' refined mechanical tools, which would always be made by, and guided by, fine hand techniques. This synthesis of man and machine did not represent the replacement of the artisan by a mechanical maker, or the wholesale rejection of mechanical devices, but rather the incorporation of man and machine into a self-consciously novel system of precision fabrication. This necessitated new kinds of mechanical tools built to work in close interaction with the craftsman, and new kinds of craftsmen willing to engage themselves closely and precisely with their machines. In the work of D'Orleans the machine is not an idea or a metaphor or an expression of frustration, but an extension of the craftsman; the craftsman no longer represents a profane deviation from mechanical rigidity but rather the very animating principle of an extended mechanical system. Though the vulgar artisan might still embody the gap between theory and practice, D'Orleans, by rejecting overmechanization, called attention to the role of a new kind of artisan in closing that very same gap.

"The machine," D'Orleans wrote, "always makes an abstraction, of more or less precision in its operation," by which he meant that the machine provided an approximation of the essential mathematical analytic that lay at its core.[66] D'Orleans therefore divided his analysis of the machine into two categories, essence and accident:

> The intelligent artisan, well-versed in Mechanics, will surely confirm, if he reflects as he ought, that this process requires an essential component which gives us the shape, as well as the accidental components, which are actually unrelated to mechanics. Because this Artisan knows that these accidental components, which is to say the foot or the hand of the artisan himself, serve only to give the impetus and the movement to the essentials of the machine, and they do not alter

[64]Ibid., p. 358.
[65]Ibid.
[66]Ibid., p. 380.

> to the least degree the simplicity of the machine's construction, or its function.[67]

In this way D'Orleans brought his scholasticism to bear on the problem of mechanical lens grinding, and used it to lay out an approach for balancing craft skill and mechanical assistance. The idea of the machine, derived from a mathematical analysis, was the "essence" of the system, while the physical machine and the physical artisan who worked it represented the "accidental" characteristics of the system of fabrication. How could the ideal synthesis of mechanical accident and essence be guaranteed? By creating the machine in accordance with nature, instead of trying to compel nature to behave mechanically:

> Art perfects nature, and at the same time art is raised to the highest degree of perfection that it can attain when it exactly imitates nature. These truths seem contradictory, yet they are forever found in the writings of Philosophers, there being nothing whatsoever distasteful about them if they are well understood. Because, in effect, it is true, and an infinite number of experiences prove that, when acting in extraordinary circumstances, nature may be found defective, and may then be aided and perfected in its operation by the arts. But art can surely add nothing to the ordinary operation of nature, which is always perfect, and therefore art is always at the most sublime point of perfection when it imitates nature exactly.[68]

In practical terms what could this sort of amphibious Aristotelianism mean to mechanics or the mechanical philosophy? It represented a departure from the attitude brought to machines by mechanical philosophers like Descartes. Although major figures in the new sciences asserted that there could be no "substantial difference" between the products of art and the products of nature, this commitment facilitated confusion between a mechanical metaphor and the world.[69] By reintroducing the distinction between art and nature, D'Orleans made space for the dimensions of nature that escaped the analysis of mathematical abstraction.[70] Here, in effect, was a call for the "incarnation" of the machine: the spirit of geometry would have to enter the stuff of the world. D'Orleans recognized that the machine had to emerge from the nature of things and could not be projected onto the natural world:

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[67]Ibid.

[68]Ibid., p. 379.

[69]Rossi, *Philosophy, Technology and the Arts*, p. 137.

[70]For a recent discussion of the relationship between art and nature in this period, see chap. 7 of Daston and Park, *Wonders*.

> Nature moves always along the shortest path, never multiplying the means of operation without necessity. This is a universally accepted axiom. Therefore, art, imitating nature, must do the same. As a necessary consequence men trained in mechanics hold a common view that the more the moving force of a machine is broken down by composite parts, the less perfect will be the operation of the machine.

The essential character of the machine could be discovered and demonstrated by mathematics, but the accidental character of the machine had to be shaped by experience and attention to the natural and real characteristics of materials, and the abilities of the human body.

D'Orleans divided his work on the making of lenses into three sections. In the first, lenses were made by a "free and flowing hand"; in the second, by "a flowing hand that is not free"; and in the third, "by machines that guide the hand." These different techniques were outlined in a progression from most primitive to most refined. In the section on the preparation of the lens by means of the "free and flowing hand," he described how to prepare a form and work a lens in the form by hand. The preparation of the form occupies most of the section, and the lathes designed for the purpose are heavy and simple but carefully designed (Figures 46 and 47). Only the one for grinding convex forms (see Figure 46) differs appreciably from other designs for pan-forming lathes that survive from earlier in the century, such as those of Manzini. D'Orleans' designs take into consideration numerous fine details, such as the shape of the chuck to hold the form and the mechanics of the tailstocks for advancing the work (Figure 48). This same section abounds with the fine details of lens craft, from the necessity of venting the mollette so that the heat of grinding does not separate the glass from the rosin, to more than three pages on how to prepare a fine tripoli abrasive by carbonizing the natural powder in an oven and grinding it in alcohol. D'Orleans wrote at length on the importance of keeping the barely perceptible oil of one's fingers away from the grinding surface, because the abrasives did not behave uniformly over a surface not perfectly clean. The entire grinding process, he insisted, must be performed on two lenses at a time, one a test lens, submitted to each step of the procedure first and then discarded at the end, having served only to equalize the abrasives and insure the proper adjustments of each stage before the application of the second or "fine" lens.

Most of these refined techniques, outlined in the first section on grinding by the free hand, apply also in the extensive chapters on grinding by the guided hand, where it is asserted that all the same convex and concave lenses could be ground more excellently by means

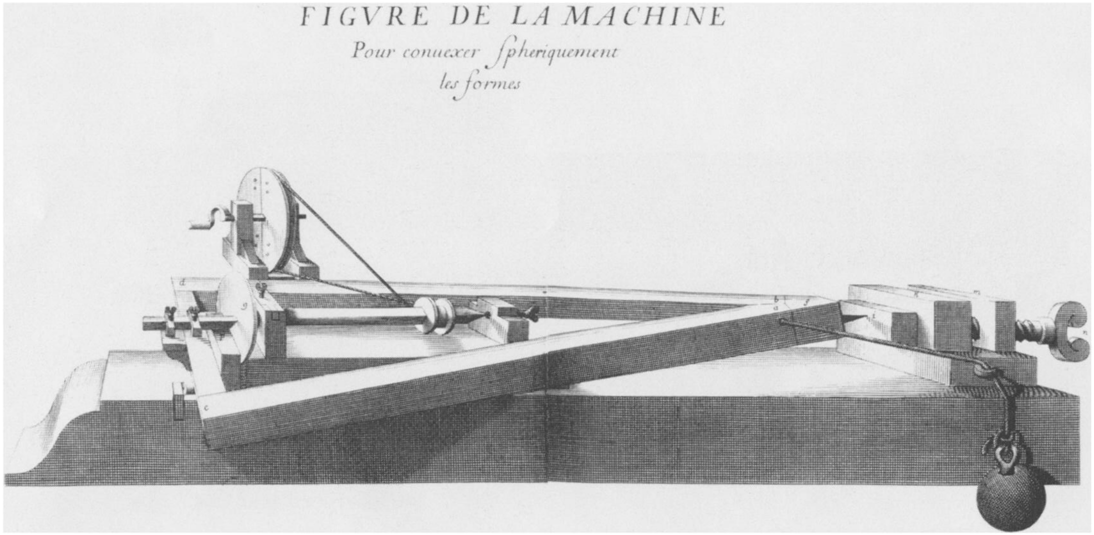

Figure 46 D'Orleans' convex form lathe (D'Orleans, *La Dioptrique Oculaire*, plate 47)

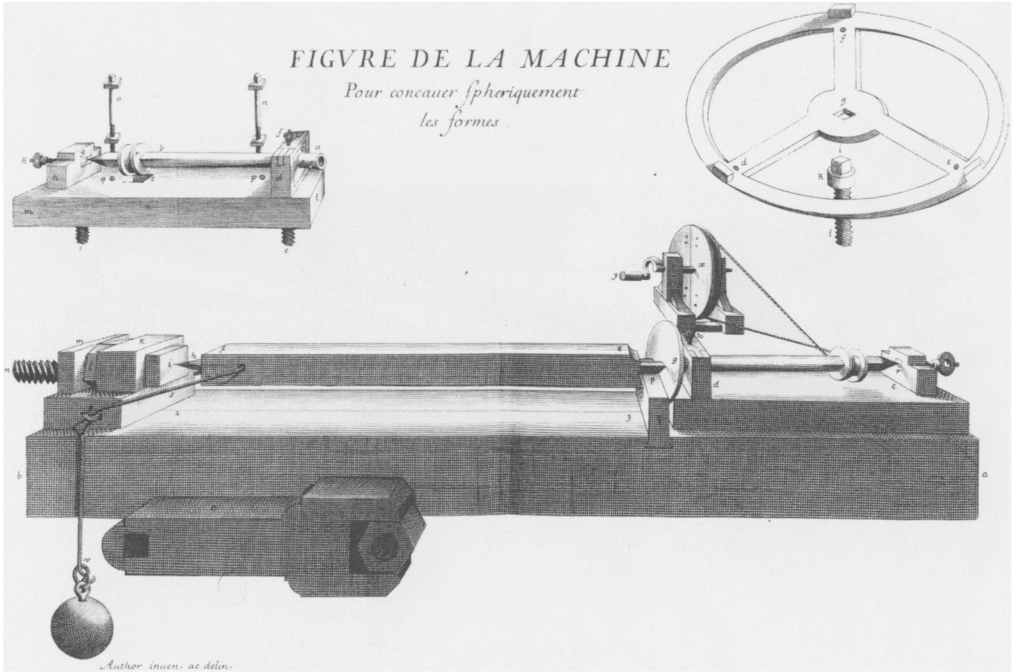

Figure 47 D'Orleans' concave form lathe (D'Orleans, *La Dioptrique Oculaire*, plate 46)

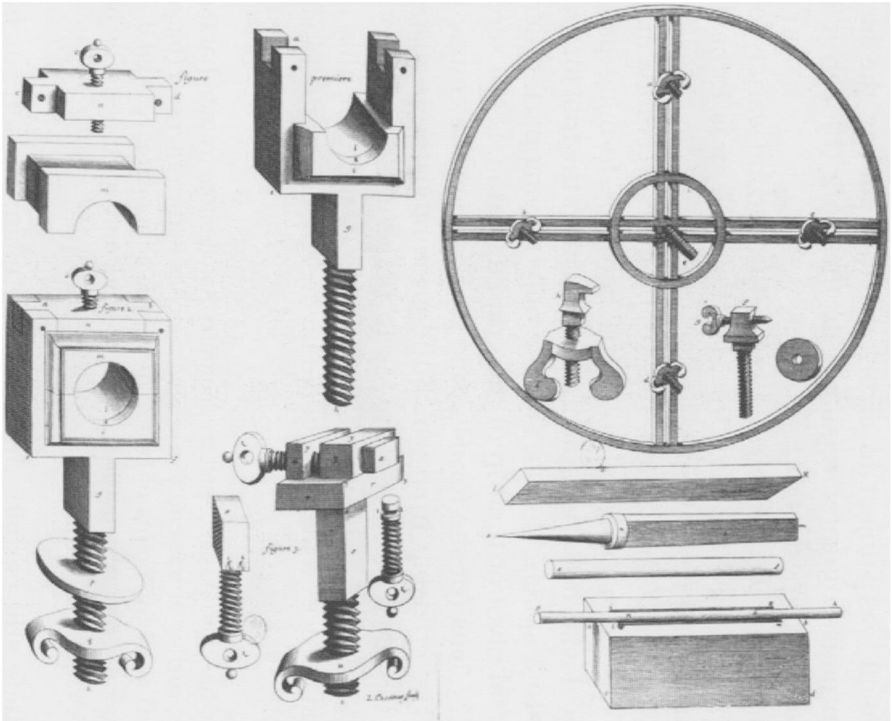

Figure 48 D'Orleans' detailed fittings (D'Orleans, *La Dioptrique Oculaire*, from plates 44 and 45)

of a mechanical tool, "while retaining all of the advantages of the techniques already described."[71] D'Orleans promised that the mechanical device guiding the hand would be "entirely exempt from the faults that the free-hand technique can allow, being freed from the direction of the hand of the artisan in the work." Though he did not suggest that the hand could only be a source of error, he did recognize that the free hand was subject to error, and that guiding the hand by machine promised greater regularity in the work (though it by no means guaranteed perfection).

The machine (Figure 49) by which the second variety of lens making—that of the hand "not free, but flowing"—was to be guided bears a superficial resemblance to the upright grinding machines of Huygens (Figures 37 and 38, pp. 100, 101). This more subtle machine, however, has been designed to shape both the forming pans and lenses. The device does not spin the lens blank or the tool for grinding the pan into a spherical dish, and the only moving part, other than the universal pivot at the top of the grinding baton, is the screw for lowering the lens (or the form-cutting tool) during the course of the grinding. The crossbar from which the grinding baton is suspended has been designed in such a way as to be adjustable and to admit lenses of different focal lengths. D'Orleans claimed that this device exemplified the way a machine could be designed in perfect imitation of nature:

> Nature has made us see, just as geometry has demonstrated, that the radius, resting at one end at a center, touches at the other end (being moved) at all the points of concavity on the circumference. And it is this that art, imitating nature, shows us how to do most perfectly by this machine.[72]

This machine still permits the artisan a "main coulant," or flowing hand, even though the movements are not free, but guided by the mechanism.

The epitome of D'Orleans' lens making systems appears in the third section, in which the hand is "ni libre, ni coulant" but rather "ruled and directed" by the mechanism. There is a set of these devices, including one of them for working small ocular lenses (Figure 50) and another for working larger objectives (Figure 51).[73] The striking

[71]D'Orleans, *La Dioptrique Oculaire*, p. 374.

[72]Ibid., p. 373.

[73]It is worth noting that in this final section D'Orleans takes up the old problem of grinding lenses by lathe without the use of a form (see note 38 in chapter 1, p. 14). Figure 51 depicts a lathe he claims is capable of such work on medium-sized objective lenses.

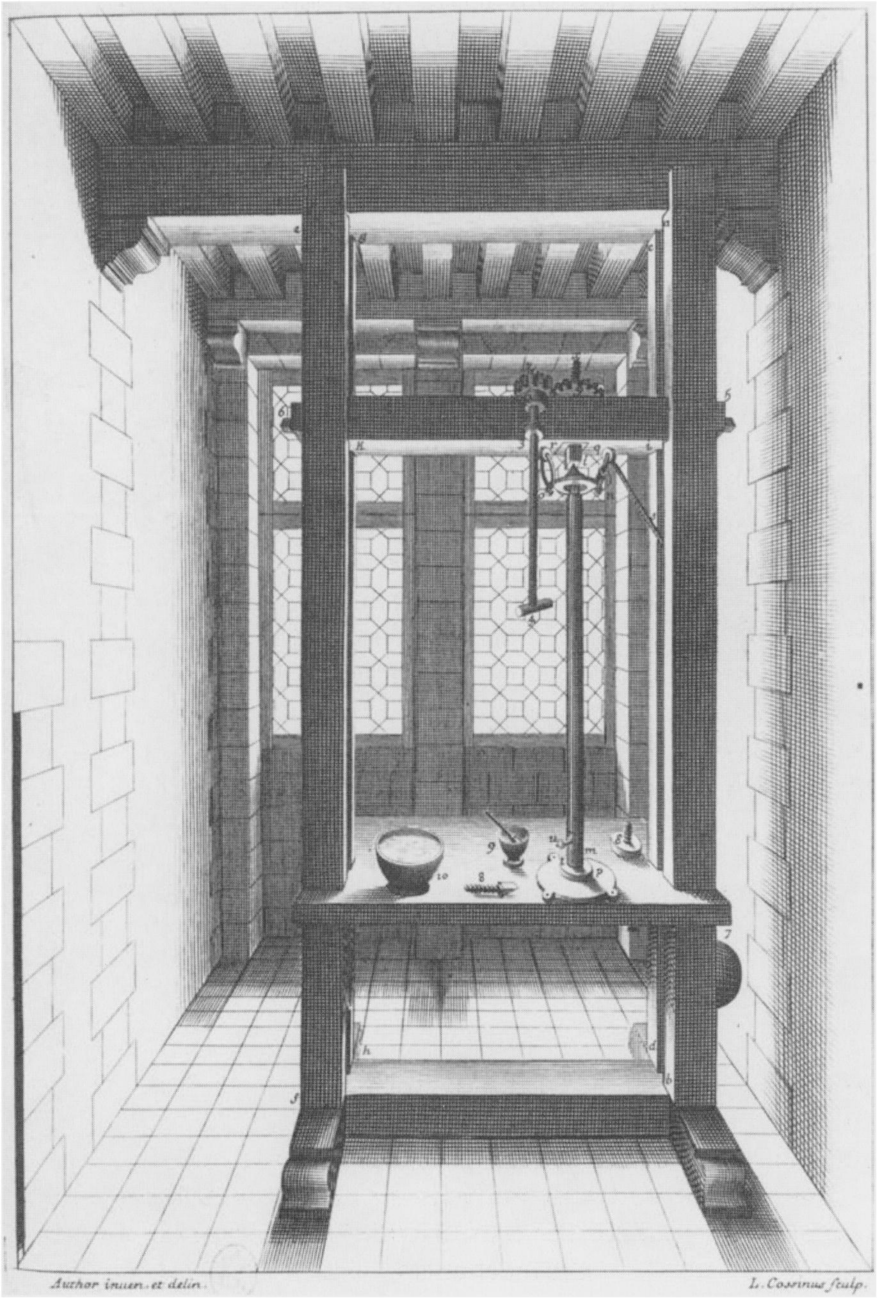

Figure 49 D'Orleans' vertical baton (D'Orleans, *La Dioptrique Oculaire,* plate 51)

characteristic of these designs is the development of an articulated "turret" for holding the cutting tool, or in some cases the work itself (Figure 52). These complex devices have a range of motions (by means of pivots, set screws, and worm gears), and enable the work of cutting

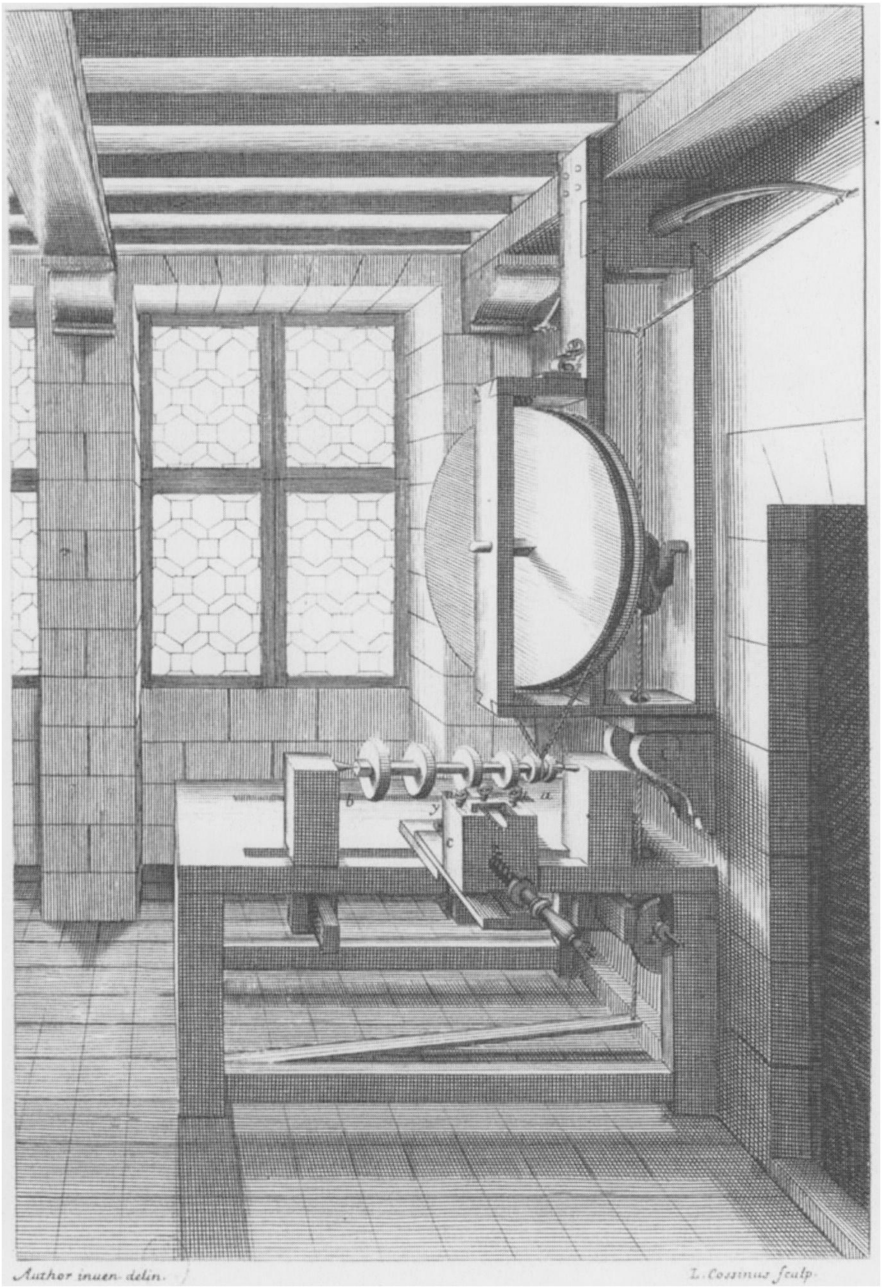

Figure 50 D'Orleans' turret lathe for small lenses (D'Orleans, *La Dioptrique Oculaire*, plate 50)

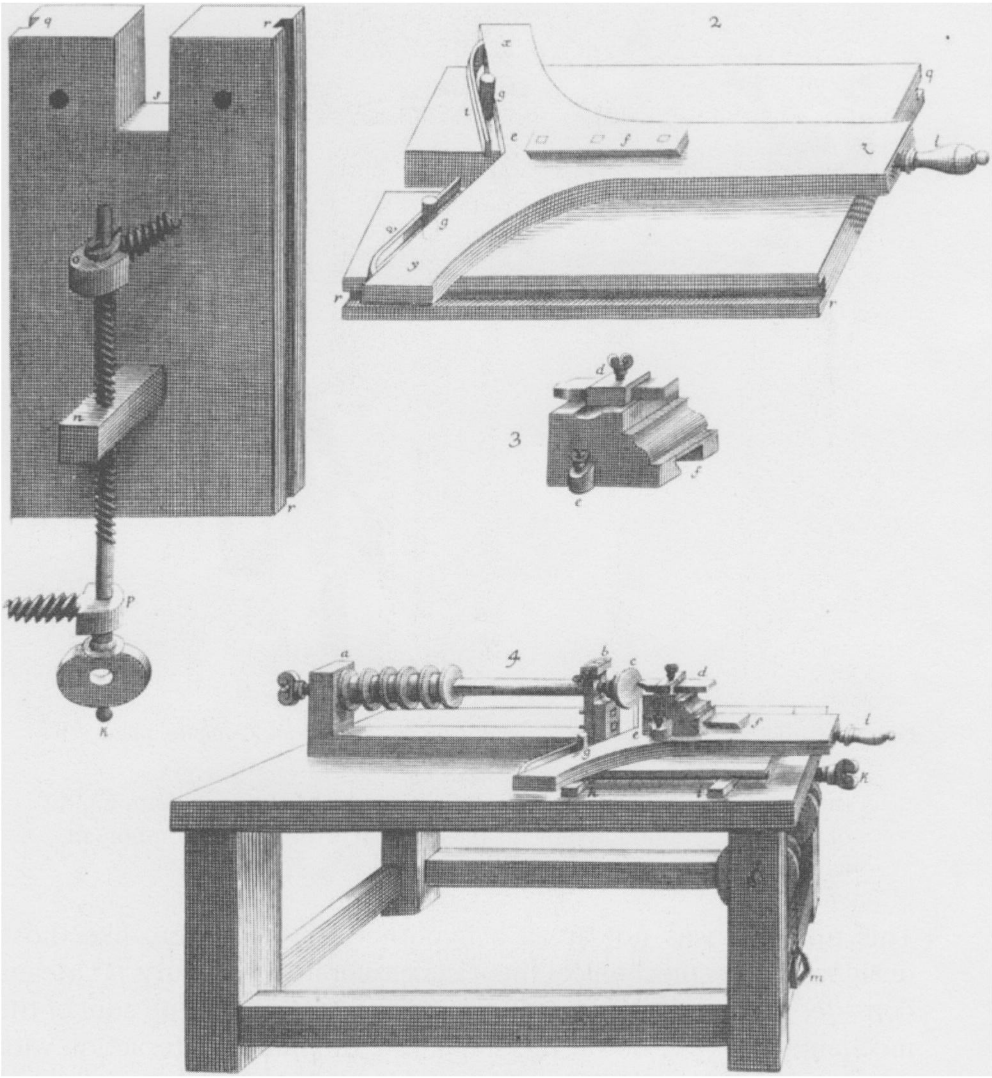

Figure 51 D'Orleans' turret lathe for objective lenses (D'Orleans, *La Dioptrique Oculaire*, plate 59)

a form (or positioning the work against a form) to be carried out by means of the manipulation of an established set of mechanical parameters. In this sense, these systems represent some of the very earliest precision grinding systems, where the work is controlled by a fully articulated rest.

D'Orleans, interestingly, did not consider this rigid mechanization of the manipulation of the lens "unnatural":

> The use of this small machine, to hold the glass lens and conduct it during the work, is not at all so absolutely artificial, that it cannot at

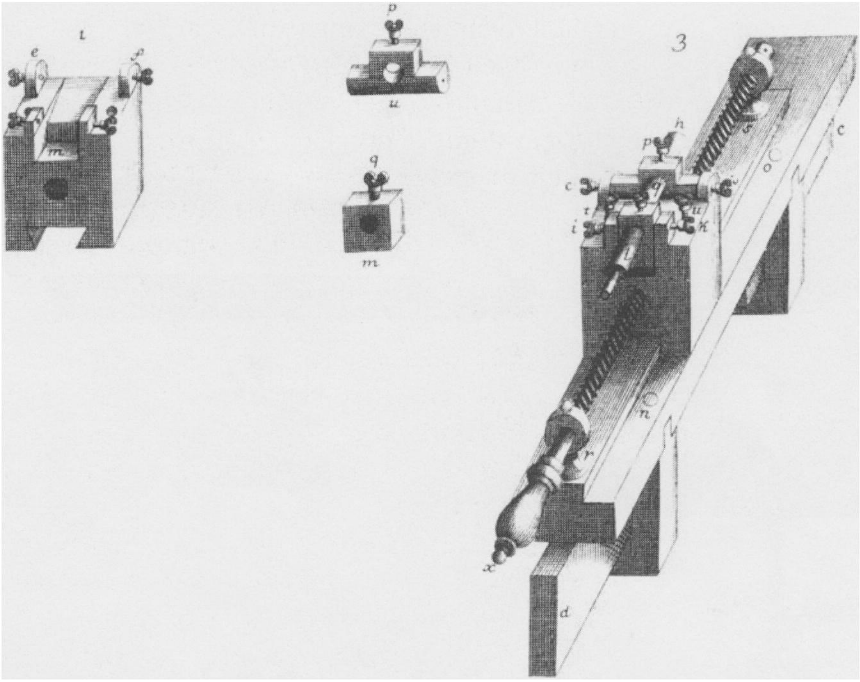

Figure 52 D'Orleans' turret fittings (D'Orleans, *La Dioptrique Oculaire,* plate 57)

> the same time be considered very natural, as it is the animate hand of the artisan, conducted by his reason, that is the central component, as I will show.[74]

This machine was not at all a hypothetical automaton, like those designed by the mechanical theorists earlier in the century. D'Orleans considered the artisan's hand and mind to be the animate soul of the mechanical device, but at the same time the human interaction with the making process had to be thoroughly mediated by the mechanical articulation of the system. The artisan was the maker, but he had to make through the machine, which had to be an extension of himself, just as he had to become a "component" within it. The successful system for making had to bind the artisan, the mechanism, and the analytical "essence" into a tight unit, a unit necessitating the mechanization of the artisan himself.

One can understand D'Orleans' contribution to the history of lens making this way: though natural philosophers' efforts to mechanize the manufacture of optical devices did not lead to banishment of the

[74]D'Orleans, *La Dioptrique Oculaire*, p. 401.

craftsmen from the process of lens fabrication, they did lead to a new kind of mechanical discipline for a new kind of artisan. The mechanical philosophy could not free itself from a dependence on the craftsman, but it could incorporate him into a mechanical system, and in doing so lay the groundwork for systems of precision machining and artisans who worked through their machines.

Conclusion: Doubting Artisans and Hyberbolic Doubt

DOUBTING ARTISANS

This book set out to tell a story about lens making in the seventeenth century and particularly about an enduring project to make telescope lenses by machine. The telling of this story has provided evidence for the origins of a new type of craftsman and a new type of machine during the period: the new machine was the articulated, precision machine tool, the device that was to play an increasingly significant role in the two centuries that followed and that would eventually stand very close to the center of the industrial revolution; the new craftsman was the antecedent of the machinist, a precision maker who had internalized mechanical imperatives and could be distinguished from freehanded artisans like spectacle makers, smiths, and glassblowers. Although the mechanical lens making systems designed in the seventeenth century never produced quality lenses with the turn of a crank, they did press craftsmen and theoreticians alike to consider in new ways the utility and advantages of mechanical systems for making. By continually representing mathematical dreams in mechanical forms, theoretical machines expressed the demand for a new kind of maker, a demand that motivated Cherubin D'Orleans and others to conceive of new interactions between man and machine, interactions aimed at yielding more precise craftsmanship. Though the artisan could not (yet) be replaced by an automatic system of production, he could be incorporated into such systems, a process that lens making pushed to a dramatic degree by the end of the seventeenth century. In this sense, though mechanical lens making machines never made lenses, they did help to create a new way of making, and a new kind of maker—both of which lay the groundwork for important changes in the eighteenth and nineteenth centuries.

The durability of the project to mechanize lens making cannot be separated from the broader structure of the mechanical philosophy, which I have tried to suggest maintained an ambivalent attitude toward craftsmen and their worlds. As the mediator between distinct and frequently discordant realms, responsible for translating the machine in the mind into the machine in the world, the craftsman, in a sense, could only fail, and this not uncommon perception of the essential inadequacy of the artisan—beyond any of his individual successes or failures—motivated seventeenth-century mechanical philosophers to attempt to design and build mechanical systems that could replace him. This aspect of the history of mechanical lens making provides something of a minor-key counterpoint to a story often told by historians about the early seventeenth century. The mechanical philosophy did not simply define a common space that could be shared by the practical arts and the theoretical sciences, a space where craftsmen and natural philosophers could coexist and cooperate in a new, synthetic relationship. The revolutionary undertakings of the period may have wedded head and hand, but the project to mechanize lens making betrays the very real struggles that attended this new proximity of artisan and philosopher. More research needs to be done to evoke the ambivalence that attended these new interactions between these distinct social and intellectual groups.

At the beginning of the century, Descartes believed he could dispense with the artisan by building mechanical systems, and in part he believed this was desirable, I have argued, because of his way of thinking about machines. Conflating the physical machine and the heuristic "idea-machine," Descartes' device became an ideal system of linked components powered to execute his task. Descartes made the artisan responsible for the gap between theory and praxis, and then promised to close the gap by a mechanical device. Though he did not succeed in absorbing the world into his philosophy, his indictment of the artisan endured, and the gap between theory and praxis has been, in some sense, the responsibility of the machinist-maker ever since.

By the end of the century Isaac Newton, working out of a tradition shared with Descartes, pushed the mechanical philosophy to its apotheosis by crafting a formal and extensively mathematical analytic of the universal machine. Yet instead of attempting to push the artisan out of his philosophy as Descartes had, Newton introduced his project in the *Principia* as the perfection of the artisans' craft. The ultimate mechanical philosopher was an artisan of geometry, who brought mathematical analysis to bear on the world. In calling the philosopher

the perfect artisan, crafting the perfect machine of the universe out of his geometry, Newton captured the complexity and significance of the relationship between theory, art, and artisan that had emerged in the course of the seventeenth century. He did not argue that geometry and mechanics were fundamentally the same (the Cartesian move), nor did he return to the classical distinction, in which the geometrical and the mechanical were considered incommensurable. The question of the relationship between the geometrical and the mechanical had become merely a question of the perfection of the mechanic:

> To practical mechanics all the manual arts belong, from which mechanics took its name. But as artificers do not work with perfect accuracy, it comes to pass that mechanics is so distinguished from geometry that what is perfectly accurate is called geometrical; what is less so, is called mechanical. However, the errors are not in the art, but in the artificers. He that works with less accuracy is an imperfect mechanic; and if he could work with perfect accuracy he would be the most perfect mechanic of all. . . .[1]

HYPERBOLIC DOUBT

Great philosophers, as Anthony Grafton has suggested, have not merely ideas, students, and critics—they have "primal scenes."[2] Few thinkers exemplify this claim better than Descartes, with his dreams, his overheated room, the inscrutable foreign melon that appears in his prophetic vision, a signifying object unconstrained by any obvious significance. Out of these hallucinatory encounters emerges the Descartes familiar to students of philosophy: the Descartes who cleared the Augean stables of scholasticism with the power hose of radical doubt, who started afresh with an irreducible proposition from which all seemed to follow—*Cogito, ergo sum*. Hanging the full weight of an epistemology and a theology on that observation proved tricky; hanging modern philosophy from it has proved considerably easier.

Abandoning tradition, as Descartes claimed to do, cannot be effected at all, nor can it even be feigned, without the tools of tradition itself; history is a dogged shadow, not a costume out of which a thinker may jump. In the same way, no student of rhetoric will overlook the rhetorical power of disavowing rhetoric. Working from these principles, recent scholarship on Descartes has excavated a figure considerably more complex than the figurehead invoked by those philosophers attentive to Descartes' writings but inattentive to their context. Work

[1]Newton, *Philosophiae Naturalis*, preface to the first edition.
[2]Grafton, "Descartes the Dreamer," p. 36.

on the evolution of Descartes' thought has pointed to significant shifts of focus that accompanied its development; work on the broader intellectual context of Descartes' project has brought new attention to the experimental/empirical dimensions of what has long been construed as the paradigmatic rationalist enterprise, has shown how religious traditions of introspection influenced an intellectual exercise recast (in the Enlightenment) as indifferent to theology, and has even suggested that the texts that threw over the entire philosophical inheritance as so much rhetoric may well have borrowed their structure from the teachings of Quintilian.[3]

One result of this scholarship has been a more nuanced understanding of several of the perennial questions raised by Descartes' work: the epistemological entanglements of his foundational enterprise; the meaning of his doubt; the significance of the *cogito*.[4] Probably the most valuable lesson offered by scholars who have taken Descartes' historical context seriously can be summed up in a sentence: "Descartes' metaphysical, mathematical, physical and physiological concerns . . . are so closely related that there are parts of his work where they are virtually indistinguishable."[5] Our categories for distinguishing such preoccupations, useful as they may be, can obscure our understanding of Cartesian thought. One area in which much has been gained by this more synthetic approach has been in the

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[3]Garber's *Descartes' Metaphysical Physics* and his recent volume of collected essays, *Descartes Embodied*, have been very useful to me in approaching Descartes' philosophical work with an eye on its relationship to his optics and geometry. Examples of recent works that have called for new interpretations of central elements of the Cartesian project based on new accounts of the growth and development of his thought include the following: on changes in Descartes' idea of certainty, Garber, "Science and Certainty"; on changes in the meaning of imagination, Sepper, *Descartes's Imagination*; on absence of concern with skepticism in early work, Gaukroger, *Intellectual Biography*. The pioneering studies of the place of experimentation in Descartes are Blake, "Role of Experience"; and Gewirth, "Experience and the Non-Mathematical." For a reading of the *Meditations* in the context of the Augustinian and Ignatian meditative traditions, see Hatfield, "Senses and the Fleshless Eye." See also, Jones, "Descartes' Geometry." Finally, the place of classical rhetoric in constituting the criteria of clarity and distinctness (as well as the precondition of self-conviction) has been established by Gaukroger.

[4]As here I will be concerned particularly with the doubt, some clarification is in order. Descartes deploys a comprehensive doubt in both the *Discourse on Method* and the *Meditations*, and the rhetorical term "hyperbolic" is often found in secondary literature applied without discrimination to both. Descartes himself uses the term only in *Meditations*, in Meditation 6: "non amplius vereri debeo ne illa, quae mihi quotidie a sensibus exhibentur, sint falsa, sed hyperbolicae superiorum dierum dubitationes, ut risu dignae, sunt explodendae" (Adam and Tannery, *Oeuvres de Descartes*, Vol. 7, p. 89); and admittedly not in such a way as strongly to suggest the constructive and clarifying power of this intellectual device. It is also unclear here whether he means by the "hyperbolic doubts" all the forms of doubt that arise in Meditation 1, or only the more extreme of these, sometimes called the "evil deceiver" doubt. Jean-Luc Marion, for instance, claims that there is no "hyperbolic doubt" in the *Discourse* (Marion, "Place of the Objections"). It would be interesting to know more about when and how the term "hyperbolic" came to be attached so firmly to Cartesian doubt, but I know of no effort to recover this story.

[5]Gaukroger, in the preface to *Philosophy, Mathematics and Physics*.

recognition of the central role played by Descartes' theory of perception in his treatment of epistemology. Rejecting the teleological theories of sensation that were the hallmark of scholastic philosophy, Descartes nevertheless saw an account of perception—and crucially an account of sight—as the necessary guarantor not only of the reliable correspondence between mental states and the objects that precipitated them, but also as a requisite dimension of his pursuit of (at best) a *mathesis universalis* or (at least) a defense of the applicability of an a-priori geometry to nature.[6] Descartes grounded his mechanistic theory of perception in his extremely successful mechanistic theory of optics. What role his mechanistic theory of perception played in his ambitious project of establishing an immutable and certain foundation for human knowledge has proved difficult to establish.

Martin Jay has summed up Descartes' ambiguous place in the history of visuality: for all his importance in French debates over the status of vision right up to the twentieth century, it seems impossible to say for certain if Descartes is best thought of as rejecting the apodictic value of the visual altogether, or rather creating a theory of knowledge that is the very apotheosis of seeing.[7] For a flavor of the trouble, one need only reflect on the paradoxical status of seeing and its cognate terms in the relevant passages of the *Meditations*. At first glance the meditator seems to be told to leave off any faith in sight, because all of the senses have been rendered suspect by the pair of escalating doubts invoked in chapters 1 and 2; the traditional reading demands that we understand Descartes to be spelunking in the dark night of his own soul. Within the camera obscura of the mind, now entirely shuttered, the meditator can for the first time be free from the profusion of (unreliable) images that normally cascade through his perceptual cognition. What, though, does the meditator seek in this closed room? Disconcertingly, he seeks an intuition that will announce itself by two qualities of eminently visual import: it will be *clear* and *distinct*. Moreover, this same intuition will be the product of the *natural light* of reason.

There are a number of reasons to be suspicious of an overly simplistic reading of the visualist language of the *Meditations*, and more specifically of the ocular overtones of its central "insight," the *cogito*. As Jay has demonstrated, ocular inflections of philosophical

[6]Treatments of the theory of perception and its applicability to epistemological questions include Larmore, "Descartes' Empirical Epistemology"; Maull, "Cartesian Optics"; and Schuster, "Descartes' 'Mathesis Universalis'."

[7]For Jay's discussion, see Jay, *Downcast Eyes*, pp. 69–85. For a sense of the opposing sides of this debate, see Maull, "Cartesian Optics"; and Judovitz, "Vision, Representation, and Technology."

language are so pervasive that caution must be employed when reading Platonist metaphors into overdetermined terminology. Moreover, Descartes himself, asked to elaborate on the operations of this natural light of reason, rejected the (available) metaphorical conceit, writing Mersenne: "I do not conceive [of eternal truths] as emanating from God like rays from the sun."[8] Nevertheless, the consistency of Descartes' use of visual metaphors in attempting to describe the nature of intuition (as well as deduction), coupled with the significance of his optical researches to his epistemological project, demand further attention.[9]

Take, for example, this excerpt from the *Regulae*: "For it is very certain that unregulated inquiries and confused reflection of this kind only confound the natural light and blind our mental powers."[10] At stake here, as well as in the *Meditations*, is the proper configuration of the mind; only a particular mental disposition allows the natural light of reason to make manifest the clear and distinct "visions" that are experienced as intuitions—and which are not only true, but the very starting point for truth. What configuration of the mind allows the natural light to coalesce into a clear and distinct idea? The answer—as will be obvious to those who have by this point gleaned the aim of this final section—is *hyperbolic doubt*. If once we saw, as in a glass, darkly, and if at some (beatific) point we will see face-to-face, for the time being the best we can seem to do is to see through the right kind of glass, the one that does not distort or obscure: and this just might be, at least initially, the focusing glass of hyperbolic doubt. To play out the suggestion, then: Descartes' greatest scientific success lay, from his perspective, in his systematic investigation of optics and the perfection of human vision those investigations promised; his optics presented an instantaneous light that could be focused into clear and distinct images by means of the interposition of a hyperbolic form. Descartes' greatest philosophical success lay, from his perspective, in a systematic investigation of the human mind and the perfection of cognitive operations those investigations promised;

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[8]Adam and Tannery, *Oeuvres de Descartes*, Vol. 1, p. 152 (cited in Gaukroger, *Intellectual Biography* p. 207).

[9]On the use of those visual metaphors, see Judovitz, "Vision, Representation, and Technology," pp. 67 and 68. Also of interest in considering the relationship between light in the eye and light in the mind are the following: Blumenberg, "Light as a Metaphor" (who notes the invasion of technological figures in the metaphorics of light in the early modern period); Jolley, *Light of the Soul*; and Ashworth, "Light of Reason." Mersenne plays with the double sense in a dedication to Descartes circa 1643, one that explicitly mentions the optical significance of hyperbolic and elliptical forms in the context of the law of refraction: Adam and Tannery, *Oeuvres de Descartes*, Vol. 4, p. 69.

[10]Adam and Tannery, *Oeuvres de Descartes*, Vol. 10, p. 371.

that human mind received, via the natural light of reason, an instantaneous, clear, and distinct illumination, but only by means of the interposition of another hyperbolic focusing device—the hyperbolic doubt.[11]

I do not wish to overemphasize the significance of the parallelism, tantalizing as it is. Following Gaukroger's reconstruction of Descartes' psychology, a quite elaborate extension of the hyperbolic(lens)/hyperbolic(doubt) analogy would be possible. In Gaukroger's reading, the imagination mediates between the pure intellect and the realm of the senses, and the experience of cognition inheres in this intermediate faculty, which represents the content of the intellect and the content of the senses both as "imagination." Where these two map onto each other the experience is that of "perceptual cognition."[12] As the project of hyperbolic doubt is abundantly imaginative, and as Descartes has insisted that the natural light of reason does not stream down from God but is within our intellects, it would be possible to argue that the imagination plays the role of the focusing hyperbolic lens, and receives the light emanating from the intellect, which normally enters the imagination confusedly, quickly distorted by the "blinding" profusion of imagery from the senses.

For all the appeal of this micromechanics of metaphor, the smatterings of textual support for it bear with great difficulty the weight of an interpretation that would seem to give us a very unfamiliar Descartes, one mucking about, Fludd-like, with a Neoplatonic master analogy. Skeptics would be right to point out that Descartes uses the term "hyperbolic" for his doubt only in the *Meditations*, not in the *Discourse*, though that text was written when hyperbolic lenses were very much on his mind and was published with *La Dioptrique*, which introduced these new optical devices to a wide audience. Moreover, the term "hyperbolic"—though it has come to be inseparable from the Cartesian idea of doubt—seems to have been used by him in reference to the doubt only once, at the end of the sixth meditation.[13] Surely if the elaborate figuration of the doubt as an analogue of his anaclastic lens had been in the front of Descartes' mind, it would have

[11]The rhetorical term—from a composition of words meaning, roughly, "over" and "throw"—is the older one, and it is found in both Aristotle and Isocrates. The derived geometrical sense originates in the *Conics* of Apollonius of Perga, and the rationale for the appropriation lies in Apollonius' taxonomy of the conic sections, which is based on the comparison of areas constructed out of particular parameters of each curve: where the "hyperbolic" curve was concerned, one of these constructed areas consistently "exceeded" the relevant comparison area. For more on this topic, see Mahoney, *Mathematical Career*, pp. 113–15; and Dijksterhuis, *Archimedes*, p. 62, n. 1.

[12]Gaukroger, *Intellectual Biography*, p. 172.

[13]See n. 4, supra.

found its way closer to the front of his texts. Hyperbolic lenses, it would appear we must conclude, were *on* Descartes' mind, but he never thought they were precisely *in* it.

Nevertheless, the coincidence stands: Descartes had spent more than a decade working on hyperbolic lenses by the time he came to draft the *Meditations*; in them, he claimed to have discovered a means of bringing the intellect to form a clear and distinct idea out of the natural light of its reason; he called this means *hyperbolic* doubt. Needless to say, the rhetorical sense was almost certainly uppermost in his thinking at the time (this was an *exaggerated* doubt, an *extreme* doubt), but just as the likely rhetorical origins of the terms "clear" and "distinct" do not erase their visual connotations, neither does the obvious rhetorical derivation of the term "hyperbolic" require us to disavow all possible connection to Descartes' celebrated optical investigation of the hyperbola. After all, this was a man who had experimented with a camera obscura that used an animal eye as its lens, and who conceived of that lens as hyperbolic in form. A scholar with such experience presumably used the expression "the mind's eye" with considerable care, and with at least a thought in the direction of the hyperbola.[14]

Situating the hyperbolic doubt in the context of Descartes' more tangible exercises with the hyperbola may serve as a useful corrective to a traditional account of the doubt that has rightly come under criticism in several recent studies. Out of the broader interpretation of Descartes' most important mathematical and philosophical work as the product of his encounter with skepticism, there arose a tendency to think of Cartesian doubt as "corrosive," as a kind of cognitive solvent responsible for dissolving all contingent truths in the quest for an immutable and resilient kernel of immanent truth. Descartes' own language—particularly that of the *Discourse*, which suggests that all must be razed in the pursuit of a firm foundation—clearly indicates that this reading cannot be dismissed, just as the anti-skeptical dimensions of Descartes' writings cannot be overlooked. At the same time, neither should all of this be overemphasized. Probably the most fundamental revision of the recent work on Descartes has been a reappraisal—and a considerable diminishment—of the importance of skepticism in Descartes' formulation of both his physics and his philosophy. Along with this has come the start of a revisionist account of the doubt itself. What has emerged are several different accounts

[14]Reading *Meditations* 6, paragraph 2: "sed simul etiam istas tres lineas tanquam praesentes *acie mentis* intueor" (emphasis added). Note this reference is indeed to the imagination, not the intellect.

of the doubt and its function, which, though emphasizing different dimensions of its rhetorical function and historical lineage, share a commitment to seeing the doubt less as a merely destructive agent, and more as a generative conceit.[15] Gaukroger has pointed out that the skeptical stance of Cartesian doubt, rather than serving to equalize and ultimately disperse cognitive commitments (as in the Pyrrhonian tradition), instead served to *direct*, even *focus*, the intellect on a single presiding question: How does the human know the divine?[16] In Gary Hatfield's insightful examination of the *Meditations* in the context of the Christian traditions of meditation proper, this revaluation of the doubt is particularly evident. Here, in the Augustinian mode, the process of doubting is a process of turning away from the senses in an effort to see the immutable divinity with the "fleshless eye" of the mind. In both of these readings the doubt emerges as a tool for good thinking, as the instrument by which an intellect overly accustomed to manipulate images derived from the senses comes to be perfected. The doubt *generates* the clear and distinct conception of the *cogito*. Understood in this way, the parallel between *La Dioptrique* and the *Meditations* becomes still more clear: *La Dioptrique* shows how the eye can be converted from a simple tool of worldly survival into an instrument of knowledge of the world; the *Meditations*, it could be offered, shows how the mind can be converted from a simple tool of worldly survival into an instrument of knowledge of the divine. Parallel clarities are required; analogous hyperbolics must be applied.

Positioning Descartes' hyperbolic doubt in the context of his elaborate exercise to generate hyperbolic lenses represents an extension of the broader efforts to understand what have come to be thought of as purely epistemological problems in terms of Descartes' more general theories of perception, which were heavily influenced by his early successes in optics. As such, I hope this epilogue (and, indeed, much of this book) can contribute to the growing recognition of the significant connections among what have sometimes been thought of as discrete dimensions of Descartes' work. The philosopher's Descartes was also a man with very particular ideas about machines and artisans. A number of connections remain to be drawn. Just one more: a celebrated passage of the *Regulae* compares the Cartesian method with a foundational problem in the mechanical arts—the requirement that a blacksmith make the tools of a blacksmith without a blacksmith's

[15]In addition to the works already cited in this respect (Hatfield, Gaukroger), I would here add Carriero, "Second Meditation."

[16]Gaukroger, *Intellectual Biography*, p. 318.

tools.[17] Here the essential quality of an epistemological problem is presented in terms of mechanical making. Is it coincidental that this passage dates to roughly the time of Descartes' earliest work on lenses? Can the lens making machine be thought of, in a sense, as an *epistemological* instrument: a tool for making tools; a tool that guarantees that your tools will work?

Such speculations may appear extravagant. But there can be no doubt that the attempt to make a machine to make lenses made a considerable impression on the philosopher of the *Meditations*. Descartes wrote the *Meditations* between 1638 and April of 1640.[18] Recall that by December of 1638 the turner of Amsterdam had completed a full-scale model of the machine, a machine that was turning out lenses (though poor ones) by September of 1639. From March of 1639 forward Descartes had Florimond De Beaune so obsessed with the machine that he wrote of having no time for anything else. No time, that is, until his crippling accident while cutting a hyperbolic glass in January 1640, just when Descartes must have been completing his manuscript. Against this background, the collapse of Descartes' project laid out in detail in chapter 2 of this paper, can there be any doubt what was on Descartes' mind as he offered yet another mechanic's metaphor in the opening synopsis of that text? Seeking to explain his ontological proof for the existence of God, Descartes offered nothing less than a subtle justification of his hyperbolic quest:

> [H]ow can the idea that is in us of a supremely perfect being have so much objective reality that it can only come from a supremely perfect cause? This is illustrated in the Replies by a comparison with a very perfect machine, the idea of which is in the mind of some craftsman. For, just as the objective ingeniousness of this idea ought to have some cause (say, the knowledge possessed by the craftsman or by someone else from whom he received this knowledge), so too, the idea of God which is in us must have God himself as its cause.[19]

[17]Ibid., p. 155. See also Garber, *Descartes' Metaphysical Physics*, pp. 41–42.
[18]Gaukroger, *Intellectual Biography*, p. 336.
[19]Adam and Tannery, *Oeuvres de Descartes*, Vol. 7, pp. 14–15. The translation is from Cress, *Discourse on Method*, p. 55.

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Index

"...if you have a year or two to apply yourself to all that is necessary, I would hope that we might see, by your efforts, if there are animals on the moon..."

With this alluring suggestion, penned in the autumn of 1629, the distinguished natural philosopher René Descartes enticed a young provincial artisan to undertake an unprecedented and secretive project, one that promised to revolutionize early modern astronomy. Fresh from enormously productive investigations into theoretical optics and applied geometry, Descartes believed he had conceived a new kind of telescope lens, shaped by the light of reason itself, and surpassing anything ever to come from the hands of the glass-working craftsmen of the era. And the superiority of these novel lenses would lie exactly in their never being touched by those hands—Descartes' lenses would instead be cut by an elaborate machine, a self-regulating and automatic device capable of bringing crystalline geometry to the muddy earth. This study traces the inception, development, and finally the collapse of this ambitious enterprise, which absorbed the energies and attentions of a broad range of seventeenth-century savants, including Huygens, Wren, Hevelius, Hooke, and even Newton. Examining in detail the making of lenses over a crucial century, *Descartes and the Hyperbolic Quest* sheds light on the history of telescopes in a tumultuous period, on the changing relationship between instrument makers and mathematical adepts, on the mechanical philosophy and its machines, and finally on the life and thought of Descartes himself.

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